ELECTRICAL ENGINEERING

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1944

The Cover: WAVES now operate the control tower of this large eastern United States Naval air station. Official United States Navy photo

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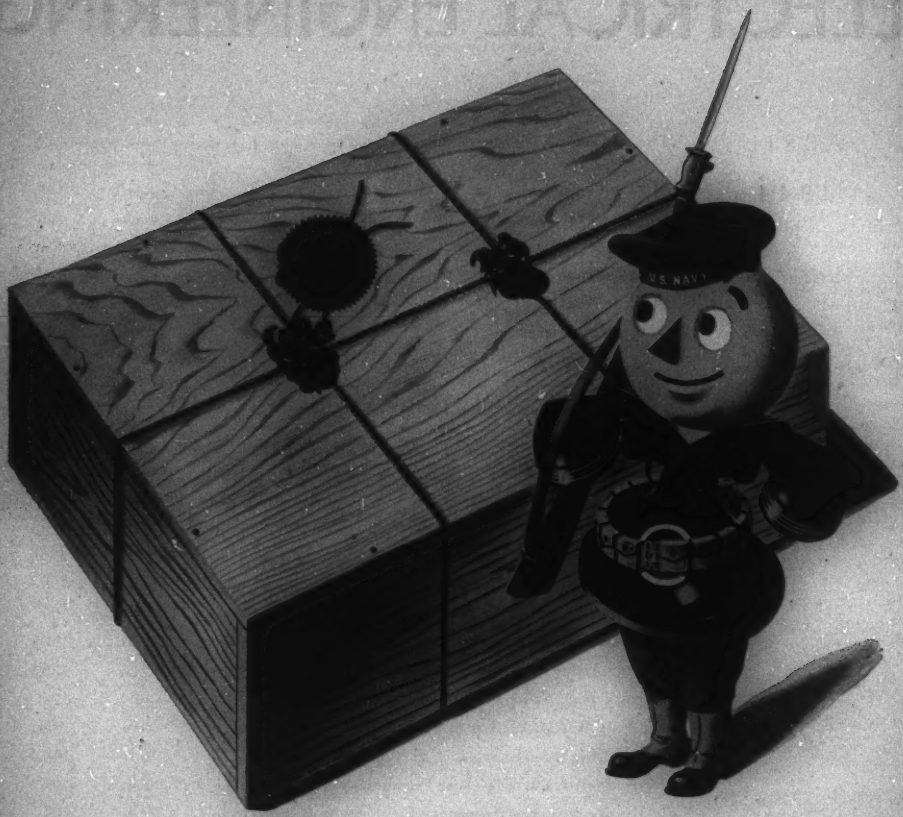

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ELECTRICAL ENGINEERING
VOLUME 63, NUMBER 4 APRIL 1944

Air Traffic Control

GLEN A. GILBERT

Air passenger traffic will increase five times and air cargo 30 times by 1950, predicts this authority in the field of air traffic control. He indicates that further advancement and comprehensive planning are needed if air traffic control is not to hamper the future development of air transportation.

IN ANY DISCUSSION of air traffic control, it is important to keep clear the distinction between *airway* and *airport* traffic control. Airway traffic control extends out along all the airways crossing the country and functions by *advance planning*. Airport traffic control is localized to a small zone around an airport and functions by caring for *immediate* situations. Thus, airway traffic control might be compared to the railroad dispatcher regulating the movement of trains along the routes between terminals, and airport traffic control to the yardmaster regulating the movement of trains into and out of the yards and shunting trains about a terminal. Both have important functions, and the transition from one to the other must be effected smoothly and efficiently. Integration of *airway* and *airport* traffic control forms one service—*air traffic control*.

The primary purpose of air traffic control is the same as surface-vehicle traffic control—protection of life and property by avoidance of collisions. This is accomplished along the airways by airway traffic-control centers and at busy airports by airport traffic-control towers. Providing safety, however, is not the only purpose of air traffic control. Although safety comes first, just as important a purpose from the standpoint of mature air transportation is the expeditious movement of traffic. Air traffic control must be designed to keep traffic flowing evenly and with as little delay as possible. Air traffic control must organize the movement of air traffic so that airports are available for business and space in the airways is not going idle while pilots are waiting to fly.

PILOT REQUIREMENTS FOR AIR TRAFFIC CONTROL

The air traffic rules of the civil air regulations establish two types of flight based on weather conditions. One is flight in accordance with "contact flight rules" and the other is flight in accordance with "instrument flight rules." Flight in accordance with contact flight rules may be described as "clear-weather flying." These rules govern flight in weather conditions where the pilot can navigate by visual contact with the ground and landmarks along the ground, and where the visibility is such that the pilot can see other aircraft soon enough to avoid collision. Aircraft flying under contact flight rules need to comply only with general rules of the road and are not subject to ground control, except at busy airports. This control is provided by airport traffic-control towers, 110 of which are today being operated by the Civil Aeronautics Administration.

The other type of flight—flight in accordance with instrument flight rules, may be described as "bad-weather flying" or "blind flying." These rules govern flight in weather conditions where the aircraft is being flown in or above cloud formations or where the visibility is not sufficient to permit pilots to see other aircraft soon enough to avoid collision. Pilots flying under instrument flight rules are subject to strict ground control. This ground control is exercised in the continental United States by 23 airway traffic-control centers of the Civil Aeronautics Administration, each of which controls an area averaging 1,600 miles of civil airways.

The instrument flight rules require that a pilot, prior to taking off, must submit his flight plan to the appropriate airway traffic-control center and receive approval for the proposed flight. In flight, the pilot must report his time and altitude over radio fixes and must comply with traffic-control instructions issued by the airway traffic-control centers. All classes of aircraft flying the civil airways under instrument flight rules are subject to this control, including airline aircraft, private aircraft, and Army and Navy aircraft.

GROUND AIDS FOR AIR TRAFFIC CONTROL

The radio navigation facilities of the United States have been planned, developed, and established in accordance with the theory that the ordinary work and responsibility of navigating any particular aircraft should be that of the pilot himself. These facilities are constructed and installed so as to provide an elaborate network of routes and markers, continuously operating regardless of the amount of traffic. This network permits a pilot to guide his own aircraft between any two points, much as a motorist with a road map can find his own way easily from city to city.

A system of radio ranges forms the skeleton of the civil airways of the United States so that, insofar as possible, an uninterrupted radio-range-course path is provided for a pilot flying along the airways. In addition to the directional guidance provided by the radio ranges, pilots are able to determine their position along the airways by means of radio "markers."

Essential substance of an address presented before the transportation group of the New York Section of AIEE, in New York, N. Y., January 12, 1944.

Glen A. Gilbert is chief of the air traffic control division, Civil Aeronautics Administration, Department of Commerce, Washington, D. C.

To make possible the control of air traffic, an extensive network of air–ground and point-to-point communication facilities is necessary. The majority of domestic air–ground communication is accomplished by two-way radio telephone. Ground stations are operated by the Civil Aeronautics Administration, military agencies, and commercial airlines, each rendering a specific type of service.

The Civil Aeronautics Administration operates those voice-radio communication facilities which are a part of the navigation facilities. That is, each radio-range station has, in addition to its navigation signals, a voice channel operating on the same frequency. This permits a pilot to receive both navigational guidance and voice communications over one radio receiver.

To connect the various communication facilities with airway traffic-control centers, a total of approximately 35,000 miles of leased telephone lines is provided, serving over 1,600 individual stations. These facilities are used to collect information concerning the movement of aircraf and to send out instructions from the traffic-control centers for relay to pilots by the appropriate radio station.

Each airway traffic-control cen er is connected to the adjoining center by teletype circuits over which messages are transmitted concerning the flow of traffic from the area under one center to the area under another center. At present over 11,000 miles of these circuits are in operation, and during 1944 it is expected that the Civil Aeronautics Administration will extend this service to a total of approximately 25,000 miles in order to handle the increasing air traffic loads.

AIR TRAFFIC SEPARATION

As pointed out earlier, airway traffic control is provided by airway traffic-control centers and airport traffic control by airport traffic-control towers. An airway traffic-control center issues traffic clearances and control instructions to aircraft flying under instrument flight rules within the limits of the civil airways in its control area. It prevents collision between aircraft by establishing vertical separation, time separation, or lateral separation. These three types of separation mean, in effect, that each aircraft is protected from collision with other aircraft by virtue of operating in a reserved constantly moving portion of the air space which is approximately 30 miles long (based on ten minutes flying time at an average of 180 miles per hour) five miles wide (one-half the width of the civil airways) and 1,000 feet high (minimum vertical separation provided pilots when visibility is less than one mile). The traffic clearances issued by the airway traffic-control centers include the points to and from which an aircraft is cleared, approved altitude level at which flight is authorized, holding instructions when necessary, approach instructions, and the time pilot may expect to receive permission to land when congested traffic conditions exist.

An airport traffic-control tower is established at airports where the traffic density is so great that pilots themselves cannot afford separation when landing, taking off, and taxiing. Control towers are so situated as to provide controlling personnel with an unobstructed view of the landing area and all approaches. Airport traffic is controlled by means of radio and light signals so as to provide adequate separation between aircraft while on and in the vicinity of the airport.

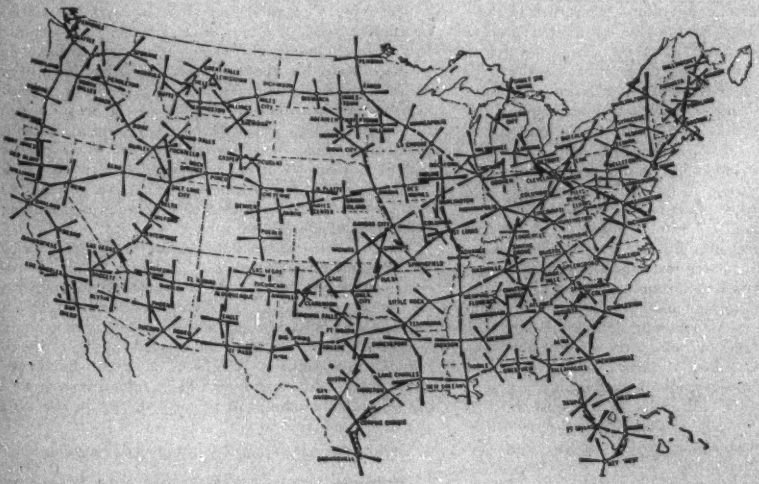

Figure 1. Radio-range system of the United States

312 radio-range stations
183 fan-type markers

PREWAR EUROPEAN SYSTEM OF AIR TRAFFIC CONTROL

So far, only the United States system of air traffic control has been discussed. It will be of interest to consider briefly systems of control outside the continental United States. The countries of prewar Europe, in contrast to this country, had no established airways. The basic system of air navigation was that of radio direction finding. This system required that ground stations take bearings on the aircraft at frequent intervals and forward them to the pilot in order that he might follow the desired course. Practically all of the air–ground communication was

accomplished by radio telegraphy, using international *Q* signals.

Shortly before the outbreak of the war in 1939, the English system of air traffic control became somewhat similar to that of the United States in that "control areas" and "inner controlled zones" were established in some sections. Aircraft within the control area were required to report before entering a cloud formation or conditions of bad visibility; to give position, height, and track; and subsequently to report any alteration. Aircraft were not allowed to enter the inner controlled zone nor to land without the permission of the control officer in the control tower.

ENGLISH WARTIME SYSTEM OF AIR TRAFFIC CONTROL

In describing the English wartime system of air traffic control, obviously, no information can be revealed which has not already been released or is a matter of common knowledge. Basically, the flying-control organization of the Royal Air Force is responsible for control and safety of all air traffic from the time of departure from the hangar or dispersal point until the aircraft has returned and is again at a hangar or dispersal point. The RAF flying control provides two methods of control over aircraft—local control, comparable to United States airport traffic control, and sector control, comparable to United States airway traffic control. One of the main purposes of the Royal Air Force flying-control organization is the provision of navigational guidance for aircraft to and from military objectives and the dispersal of arriving aircraft to airfields where the most favorable conditions exist. Information available indicates that air traffic control as known in this country—that is, the issuance of instructions for the prevention of collisions between aircraft—is exercised only on and in the vicinity of landing areas and then, as a general rule, mainly under contact weather conditions.

SYSTEMS OF AIR TRAFFIC CONTROL IN WESTERN HEMISPHERE

The systems of air traffic control in the Western Hemisphere vary from little or no control in South and Central America to the highly developed control system north of the United States–Mexican boundary. In general, no control is provided except by infrequent airport traffic-control towers, in Mexico, Central America, and South America, whereas the United States, Canada, and Alaska follow the system described for the United States.

LIMITATIONS OF PRESENT AIR TRAFFIC-CONTROL SYSTEM

Let us next consider limitations of the present United States system of air traffic control. At first glance, it might be thought that *safety* is the sole standard which would define these limitations. Safety, within the inherent characteristics of the aircraft and subject to capabilities of the pilot, can always be provided. The tool of last resort available to air traffic control to achieve this result is the restriction of aircraft movements. Carried to absurdity, this means that, upon warning of the approach of bad visibility and lowering ceilings, all aircraft could be grounded, and but a single plane could be permitted to move in any one section of the country. No collisions could occur, and safety of the highest possible order would be provided insofar as the air traffic-control system is concerned.

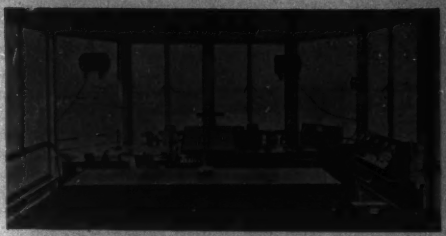

Figure 2. Airport traffic-control tower

Figure 3. Airway traffic-control center

Although safety must be provided at all times, the insurance of safety cannot be the sole standard for judging the performance of air traffic control. The standard of judgment must be based upon the *efficiency* with which traffic is safely guided.

Assuming that air traffic control does not prevent any flight from taking to the air or remaining in it, there are several possible standards for judging its efficiency. In ascending order of difficulty in achievement, these are:

1. Safe landing of all aircraft at any available point at any time.
2. Safe landing of all aircraft at intended destination at any time.
3. Safe landing of all aircraft at intended destination in scheduled or normal flight time, within reasonable limits.
4. Safe landing of all aircraft at intended destination exactly on schedule or in normal flight time.

The present standard of efficiency of air traffic control is somewhere between standard 1 and standard 2. During the next few years the standard of control efficiency must rise to number 3. The highest standard, number 4—safe landing of all aircraft at intended destination exactly on schedule, or in normal flight time—must be closely approached before air transportation can become fully mature. It can be expected that this standard will be demanded by the traveling public and the shippers in the not too distant future. The air-traffic-control system must be capable of meeting the desired standards, or air traffic control may become the one factor which will limit the utilization of air transportation in the future.

IMPROVEMENTS PLANNED BY THE UNITED STATES

A program of improvements in the United States system of air traffic control has been planned by the Civil Aero-

nautics Administration and is being activated as rapidly as circumstances permit. Included is an improved navigation system using very high-frequency radio ranges and the provision of more adequate air–ground and point-to-point communication facilities, the establishment of an automatic system for the handling of flight data required for air traffic control, and improved control procedures based on the use of the new facilities. This program of improvements is expected to increase greatly the capacity of the present air-traffic-control system by making possible more approaches during instrument weather conditions and reducing separation between aircraft along the airways.

At airports, successive landings under instrument weather conditions should be possible at three-minute intervals. Thus, the capacity of a properly facilitated airport will be approximately 20 arrivals and 20 departures or approximately 40 aircraft movements per hour. This compares very favorably with the present situation whereby airports today can handle only approximately ten aircraft movements per hour during instrument weather conditions.

Along the airways substantial reduction in time separation should be possible between aircraft flying at the same altitude. Instead of the 15-minute separation between aircraft existing on some airways today due to insufficient fixes, and a minimum of ten-minute separation on all other airways, it is expected that the improvements planned will make possible a reduction in this separation to perhaps five minutes.

This means that the plans of the Civil Aeronautics Administration which are now ready and which can be placed in effect in the immediate future will result in an increase in capacity of the United States air-traffic-control system to at least four times its present capacity.

AIR-TRAFFIC DEVELOPMENT

Will this expansion be sufficient to provide for future needs? Many estimates have been made recently as to the amount of air traffic that will develop after the war. A careful analysis of these estimates and expectations indicates several assumptions which have been generally accepted. These are:

1. Scheduled air passenger traffic by 1950 will increase to approximately 10,000,000,000 passenger-miles, or five times the present air passenger traffic.

2. Air cargo by 1950 will amount to at least 600,000,000 ton-miles of freight, express, and mail moved by air annually, or 30 times that being transported in commercial air carriers today.

3. A total of approximately 500,000 aircraft will be in service in 1950 as compared to approximately 30,000 before the war.

Based on the foregoing, it appears logical to conclude that increases in air traffic by 1950 over that existing in 1941 will be approximately 14 times for air-carrier aircraft, 18 times for private aircraft, and 10 times for military aircraft. If these expectations become a reality, it is obvious that the improvements now planned will be merely stopgaps. Further advancement in the field of air traffic control will be required in the years immediately following cessation of hostilities.

FUTURE PLANNING

Much has been said about the possibilities of wartime developments revolutionizing or at least radically changing the present system of air traffic control. The war without question has accelerated many technical developments. Special progress has been made in the field of electronics. However, application of the various principles and techniques developed of necessity has been directed entirely toward wartime needs.

It appears, therefore, that very few, if any, wartime technical developments will be immediately applicable without change to meet peacetime needs. The end of the war will bring improved technical principles and techniques, but their application to peacetime requirements will have to be worked out. Moreover, it would seem that such wartime technical developments as will be available and gradually adopted for peacetime aviation before—say—1950 will be only supplemental and assisting with respect to the present air-traffic-control system.

As an example in support of this line of reasoning, it might be pointed out that there is a widespread opinion that radar devices will greatly change air traffic control in the immediate postwar

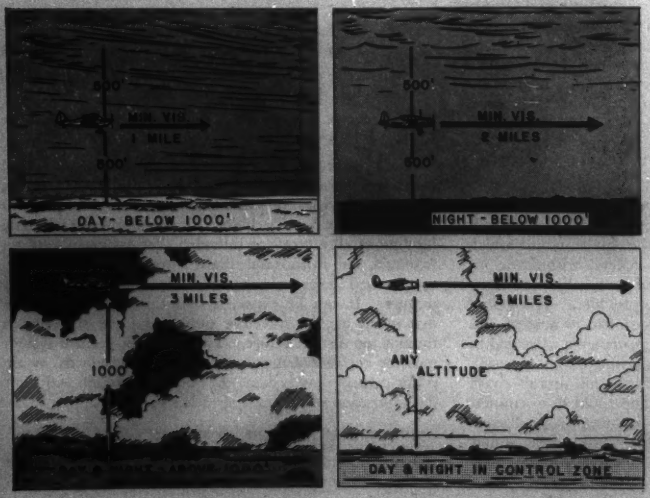

Figure 4. Contact - flight - rule weather minimums

Weather limitations for flight in accordance with contact-flight rules, illustrating visibility and distance from cloud minimums

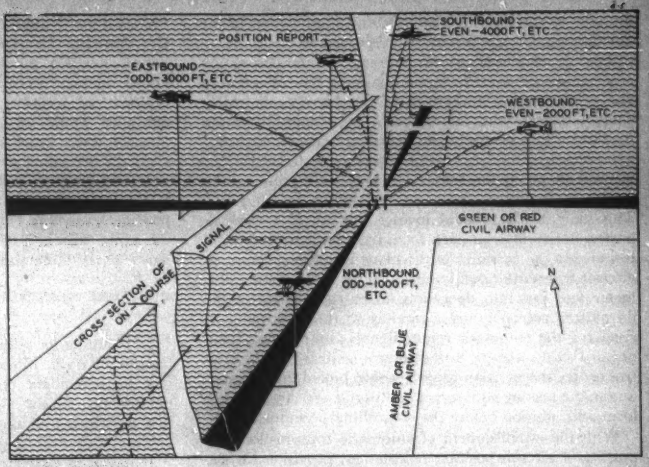

Figure 5. Flying the civil airways

When flying the civil airways by use of instruments, pilots are required to follow instructions issued by airway traffic-control centers and airport traffic-control towers. Aircraft are assigned specific altitudes and must report time and altitude at reporting fixes

period. An analysis of the principle of radar indicates that it has its main advantage in detecting the presence of objects which will not "cooperate," such as enemy airplanes and ships during wartime. To obtain such detection it is necessary to provide complicated apparatus involving high cost, substantial weight, and special technique for operation.

In the control of peacetime aircraft, however, the situation is entirely the reverse in that all aircraft *will* co-operate. In other words, devices can be placed on board peacetime aircraft which will *reveal* their presence. Thus, it becomes possible to apply a different technique for the detection of aircraft for air-traffic-control purposes in peacetime which will involve less complex apparatus, less cost, less weight, and simpler operation. Certainly some of the improved electronic techniques developed during wartime will be used for air traffic control, but application will be for peacetime requirements, meeting entirely different specifications from those existing under wartime conditions.

INFLUENCE OF WEATHER ON FLYING

In the postwar period and up to at least 1950, it is believed that weather will continue to be a factor affecting flying. Private pilots will refrain from flying during low cloud and restricted visibility conditions in the same way that the average automobile driver avoids using his car during poor driving conditions. There probably will be an increasing number of private pilots who will be qualified to fly in weather conditions requiring instrument flight as a result of wartime pilot-training programs. By and large, however, it is expected that the great majority of private pilots will continue to be "fair-weather" fliers.

Commercial air carriers can be expected to constitute the bulk of poor-weather flying after the war in the same way as they did before the war. Scheduled air-carrier service is economically successful only if conducted regularly. Hence, this type of service must operate under practically all weather conditions. Some military flying involving the larger types of aircraft probably will be accomplished in a manner comparable to the scheduled air carriers. However, it is expected that the majority of postwar military flying will be done only during the more favorable weather conditions. Air traffic control, therefore, will continue to have two types of flying to contend with—good-weather or "contact" flying and poor-weather or "instrument" flying.

FUTURE AIRCRAFT EQUIPMENT FOR AIR TRAFFIC CONTROL

In attempting to eliminate or reduce all limitations of air traffic control so as to increase the capacity and raise the efficiency of the system, several devices for installation in aircraft appear to provide possible solutions. These devices will be identified as a "collision-warning device," an "automatic-position reporter," and a "traffic-clearance indicator." The latter two devices ultimately may be combined to provide a "block signal system."

The ultimate solution for the control of the large number of aircraft anticipated in the future will require that some means be provided which will permit the shifting of a substantial amount of responsibility for the avoidance of collision from ground agencies to the individual pilots of aircraft. In other words, each pilot flying in instrument weather conditions should be able to avoid collision with other aircraft by directly observing indications of the position of the other aircraft. The means to accomplish this probably will be in the form of a "collision-warning device."

Development of one such device, identified as a "vertical-separation indicator," was commenced some time prior to the war by the Civil Aeronautics Administration. This device will permit a pilot, by reference to an instrument upon the aircraft instrument panel, to determine at a glance the vertical separation between his aircraft and other aircraft within a fixed radius and will also indicate roughly the horizontal distance between his and the other aircraft. The pilot thus will be enabled to maintain a specified minimum amount of vertical separation between his aircraft and other aircraft within a certain radius during climb, level flight, and descent.

A somewhat different device might be provided as a "horizontal-separation indicator." This instrument would be a screen on which various size dots would indicate the relative position of other aircraft located within an area ahead of the aircraft concerned, and within at least 45 degrees above and below as well as to the right and left. The size of each dot would represent the approximate

distance to the indicated aircraft and the location of the dot the angular position of the other aircraft.

The development of an automatic aircraft-position reporter would contribute materially to the reduction of one of the major limitations of the present air-traffic-control system—the use of voice as a communication medium. This device would permit an aircraft to actuate a reporting mechanism as it passes each fix along the airways in much the same way as a train trips certain signals as it passes predetermined points on its route. This plan, briefly, would involve the use of a vertical-pattern transmitter at each fix, a receiver in each aircraft to indicate the entrance of the plane into this pattern, an aircraft transmitter continuously set by a controlling altimeter and put into operation under the control of the fix pattern receiver, and a receiver at the fix capable of receiving the automatic report signals and relaying them onward to the airway traffic-control center. At the control center the position reports would be fed directly into automatic posting equipment and would appear in proper form and position before the controlling personnel.

With the establishment of automatic transmission and posting of aircraft-position reports and provision for the automatic transmission of traffic-control instructions from ground personnel to pilots, voice as a communication medium could be eliminated entirely in the control of air traffic. Such a plan involves the storage of traffic-clearance data on mechanized flight-progress boards in airway traffic-control centers and the automatic transmission of these data by radio at appropriate times to actuate a device in the aircraft which might be called a "traffic-clearance indicator."

As visualized, the circumference of the traffic-clearance indicator would be taken up by a series of lamps, one for each flight level. As the plane proceeds at an altitude for which clearance has already been received, the lamp for that level remains lighted. When a clearance to another altitude is received, the lamp for that altitude starts to flash, and the lamp in the center, over the word "change," lights to attract the pilot's attention to the fact that new instructions have been received. This light is extinguished by the pilot when he pushes the "acknowledge" button, causing at the same time the transmission of his aircraft identification and the clearance as it appears on his instrument. This acknowledgment is automatically compared at the control center with the posted clearance, and a disagreement warning appears before controlling personnel if an error is apparent.

The indicators shown in the center of the dial include "go," "hold," "change," and "taxiland." The "taxiland" light is used for airport traffic control when the aircraft is to move on the ground or to authorize a landing. "Go" authorizes a take-off or forward progress at the indicated altitude. "Hold" calls for remaining stationary while on the airport and for maintaining the indicated altitude at the next fix while en route.

It should be understood that transmissions will be made and a pilot's indicator changed only when the pilot must make a change in the procedure he has been following. In many cases only a brief transmission upon departure will be required, plus one or more in connection with landing at destination.

In the much more distant future it may be found necessary to combine the traffic-clearance indicator and the automatic aircraft-position reporter into an automatic "block-signal system" of a type similar to that used by the railroads. This system, as visualized at this time, would consist of marker transmitters producing a screen across the airways at block-signal "fixes" 10 to 15 miles apart. An aircraft proceeding along an airway so equipped would set up a "hold" signal for succeeding aircraft at the same level which would not be canceled until the preceding aircraft had climbed or descended to the next level or had passed the next block-signal fix along the route. Thus, the block-signal system would provide a warning to prevent two aircraft from being in the same "block"—the air space between two adjacent fixes—at the same altitude.

FUTURE GROUND FACILITIES FOR AIR TRAFFIC CONTROL

In planning for additional ground facilities required to control air traffic of the future, the nature of such facilities will be dependent chiefly upon the accepted aircraft equipment. If the automatic air-traffic-control devices just described are adopted, then corresponding ground facilities also must be provided.

It has been estimated that approximately 850 air stations will be required within the next few years to provide an adequate scheduled air-carrier traffic pattern. This is over three times the present number of scheduled air-carrier stops. Such a service pattern undoubtedly would require that air-traffic-control protection be afforded over all air space within the continental United States. It is not believed that the extension of air traffic control to include all air space will mean the discontinuance of civil airways. Rather, it is expected that civil airways will be continued as channels where a continuous heavy flow of traffic ordinarily exists. Flight outside of these channels will follow individual routes but, nevertheless, will be afforded air-traffic-control protection to the same extent as is provided on the civil airways.

Basically, it is expected that the radio ranges, or comparable directional facilities, will delineate the civil-airways system. Flight off the civil airways probably will be accomplished chiefly by use of automatic direction-finding facilities. With the establishment of automatic air-traffic-control devices in aircraft and with the provision of corresponding ground facilities, there appears to be but one remaining need of air traffic control which will require additional ground facilities. This is the constant portrayal of actual positions of aircraft to controlling personnel.

By the installation of "scanning screens" in airport traffic-control towers, it appears that this requirement can be met. One screen would portray the positions of aircraft in a horizontal plane within perhaps 25 miles of the airport. The aircraft positions would be indicated by a spot of light which would be moving constantly as the aircraft positions change. Another screen would show the relationship of aircraft in a vertical plane along the path followed by aircraft when approaching the airport under instrument weather conditions. A dot appearing on this screen would indicate the altitude of the aircraft and its position in the holding flight path.

FUTURE AIR-TRAFFIC-CONTROL PROCEDURES

It would be highly desirable if the automatic air-traffic-control equipment for aircraft could be light enough and cheap enough so that all aircraft flying under

instrument flight rules would be equipped with these devices. However, it is expected that, at least for a long time, only the larger aircraft will be so equipped. The most optimistic estimate would place not more than 50 per cent of the aircraft flying in instrument weather by 1950 in the category of those having full automatic air-traffic-control equipment. This means that the air-traffic-control system would have to continue to be capable of controlling a substantial amount of air traffic involving aircraft having only the minimum air-traffic-control equipment such as is required at the present time.

However, the automatic devices for aircraft and the ground aids for air traffic control previously described point to the possibility of obtaining the ultimate objective of permitting the flow of air traffic under instrument weather conditions in the same volume and with the same frequency as is possible under contact weather conditions. This means that, at an airport properly designed and adequately served by navigational and air-traffic-control facilities, landings under instrument weather conditions would be possible at 50-second intervals, or approximately 70 landings per hour per runway in use. Thus, future planning seems to indicate that it will be possible for the air-traffic-control system within the United States to reach the level of safety and efficiency which ultimately will be required by mature air transportation.

INTERNATIONAL ASPECTS OF AIR TRAFFIC CONTROL

Most expert opinion anticipates that postwar air transportation will develop internationally in substantial proportions. Extensive international air commerce in the postwar era may be an important factor in cementing all of the nations of the world more closely together. As air transportation becomes global in scope, it is increasingly apparent that worldwide standards for the control of air traffic ultimately must be established if international air commerce is to develop to the fullest possible extent. An airplane flying from Moscow to Chicago, for example,

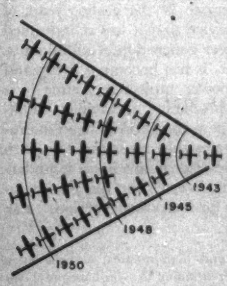

Figure 6. Capacity of air traffic-control system

Each plane indicates four instrument approaches per airport per hour. In 1943 it was possible to handle four instrument approaches per airport per hour. With improved facilities it is planned to accommodate 12 instrument approaches per airport per hour in 1945, 30 in 1948, and 60 in 1950

would pass over areas under the control of at least seven different countries. Obviously, if each country had different systems of air navigation, different flying regulations, and different systems of air traffic control, an extremely difficult if not impossible situation would result.

It is believed, therefore, that one of the most important phases of postwar planning for aviation is the planning of worldwide standards for air traffic control. Such planning should include the formulation of navigation standards, communications standards, aircraft-equipment standards, standards for flight rules and for control procedures.

CONCLUSION

The present basic system of air traffic control in the United States is expected to continue without radical change in the foreseeable future. Improvements now planned will help, but further advancements in air traffic control must be made in the next few years to meet the expected demands of postwar flying.

Military technical developments undoubtedly will become available for air-traffic-control purposes, but application will be to peacetime specifications meeting different requirements from those existing during wartime. Automatic air-traffic-control devices must be perfected which will make it possible for pilots to exercise a substantial amount of traffic separation on their own responsibility. These devices also should eventually make possible the elimination of voice as a communication medium in the control of air traffic. Comprehensive planning must be accomplished so that air traffic control, both domestically and internationally, will *not* become a bottleneck in the future development of air transportation.

Welding-Electrode Refrigeration

That electrode life can be prolonged, tip pickup retarded, and spot-welding speed increased by electrode refrigeration under good welding conditions was disclosed by recent investigations into the effects of coolant temperatures on spot-welding electrode performance. The project was directed by W. F. Hess (M '41) associate professor of metallurgical engineering and head of the welding laboratory of Rensselaer Polytechnic Institute, Troy, N. Y., the project was sponsored by the Welding Research Council of The Engineering Foundation.

A comparison of the performance of the conventional bored-cylinder electrode and a capped electrode manufactured by Frostrode Products, Detroit, Mich., revealed that water-cooled conventional electrodes lasted an average of 30 spots between tip cleanings whereas the refrigerated capped electrodes produced more than 2,200 acceptable spot welds between cleanings. Doctor Hess reported obtaining better results from the Frostrode electrodes cooled with tap water than from the conventional electrodes cooled by five times the amount of tap water held at the same temperature as that which circulated through the capped electrodes. The tests also showed that the contact face of the capped electrode is affected less than that of the standard electrode by changes in the temperature of the coolant medium because of the efficiency of heat transfer to the refrigerant possessed by the capped electrode.

However, Doctor Hess warned that refrigeration is not a cure-all for the many troubles encountered in spot welding. Neither can the refrigeration correct for faulty practices which sometimes obscure the benefits of a better cooling of the electrodes, according to the report. Alclad 24*ST* sheet, 0.040-inch thick, was the material used for the welding tests and the temperature of the refrigerant in the capped electrode was held at 0 degrees Fahrenheit. The test conditions consisted of welding as continuously as possible until the electrodes showed evidence of having been in use too long.

Recent Developments in Light Sources

PRESTON S. MILLAR
MEMBER AIEE

Recent advances in the field of illumination before the war and the probable postwar developments and applications furnish the subject of this article. Arc, tungsten-filament incandescent, infrared, mercury-vapor, sodium-vapor, and fluorescent lamps are discussed in detail.

LIGHT is usually produced through the process of either incandescence (which for this general discussion may be taken to include combustion) or luminescence. Sources brought to a glowing temperature of incandescence are usually accompanied by infrared or heat radiation and very little ultraviolet radiation. Those that produce light through the process generally characterized as luminescence are electronic devices that may produce a good deal of ultraviolet as well as infrared radiation. Generally speaking, incandescent sources provide continuous spectra, whereas luminescent sources provide line or band spectra. Indications of several responses to radiation in the ultraviolet, visible, and infrared regions are set forth in Figure 1.

Radiation between wave lengths approximately 3,800 and 7,600 angstroms stimulates the human eye to vision. This narrow band of about one octave, out of about 80 octaves of the electromagnetic spectrum, is adjoined immediately by shorter wave lengths in the ultraviolet region that are applied in producing fluorescence and for photochemical and germicidal purposes. It is adjoined immediately by longer wave-length radiation that is utilized for drying and heat therapy.

It perhaps will not be out of place to recall further that the response of the human eye to radiation within the visible spectrum varies greatly for radiation of different wave lengths, attaining to a maximum value near the middle of the visible spectrum at about 5,550 angstroms with a shift of this maximum toward shorter wave lengths as intensity is decreased. The relative luminosity curve of normal human vision has been established by the International Commission on Illumination as in Figure 2.[1] These are the accepted data for the visual response of the human eye to radiant energy of various wave lengths.

Electric lamps are available in wide variety, having different qualities that fit them for application under different circumstances for several distinctive purposes. In some respects they may be likened to the instruments of an orchestra. Each has its place. All fulfill some useful purpose. The range of sounds of the orchestral instruments from the deepest "umph" of the contrabase tuba to the shrillest note of the piccolo is of the order of seven octaves. The composer calls upon them individually and in any combinations to produce desired effects. Electric lamps produce radiation of frequencies covering a range of like extent from the longest-wave infrared of glowing bodies to the shortest-wave ultraviolet radiation. The engineer may draw upon the resources of any one or of a combination of types of radiators, according to the purposes to be served.

Electric lamps that meet more or less successfully the requirements for radiation throughout the entire optical spectrum are commercially available. Indeed, many of these requirements may be served by alternative devices that are competitive and that have different characteristics, thus affording the engineer a choice of methods. The only lack in the materials of illumination is war-begotten and temporary. For practically all forms of electric lamps have gone to war. The more essential types are still being produced, but the number of types has been halved. Development of light sources is confined to military applications. New developments for civilian use wait upon victory. Any account of advances in light sources at this time must be lacking in news value. The principal American lamp manufacturers perform exceedingly well the task of supplying to engineers informative material concerning their several products. Their technical and commercial publications are comprehensive and informative, and they have responded helpfully to every request of the author for material for this article.

Arc Lamps

This oldest of electric illuminants has an interesting and honorable record of service in the earlier years of electric street lighting—a service that it has relinquished for the most part to a younger generation of illuminants. In other directions, however, it has become a lively and useful device. As a high-power projection source it is particularly valuable. In producing ultraviolet radiation it is also important. The principal American manufacturer of arc carbons indicates that, as is the case with most electric illuminants, the electric arc lamp is undergoing dynamic development, diverted for the present to war purposes, but promising for the postwar period. For instance:

For searchlight work, experimental high-intensity carbons have doubled present-day performance, attaining to a brilliance of 2,000 candles per square millimeter, or better.

Improvements in carbons, in applicable optics, and in methods of operation promise delivery of three times as much light to motion-picture screens as is attained commercially today.

High-purity spectroscopic carbons are finding large use for war purposes in rapid checking of critical alloys for impurities. This method of analysis is used extensively in the aluminum, brass, and copper industries and is understood to be coming into extensive use in the steel industry.

The carbon arc in latest development gives a close approach to quality of sunlight in the near ultraviolet region that is most effective in photochemical reactions.[2] These arcs are used largely in ac-

Essential substance of an address presented under the sponsorship of the AIEE committee on production and application of light at the conference on lighting, AIEE winter technical meeting, New York, N. Y., January 26, 1944.

Preston S. Millar is president of Electrical Testing Laboratories, Inc., New York, N. Y.

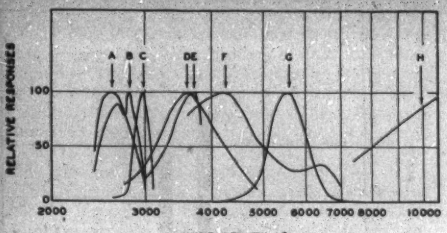

Figure 1. Some effects of radiant energy

A—Bactericidal
B—Vitamin D in sterols
C—Tanning
D—Photoprinting
E—Fluorescence—paints
F—Panchromatic film
G—Vision
H—Penetration of cheek

celerated weathering or fading tests in the protective coating, rubber, and textile industries. They are used also for the irradiation of milk, tobacco, and pharmaceutical products.

Tungsten-Filament Incandescent Lamps

In variety, range of sizes, simplicity, readiness of application, and wide acceptability, incandescent lamps are of very great importance in electrical service. American achievements in production and use of such lamps are pre-eminent.[3] The relatively low American rates for electric energy and the relatively low prices for American lamps have made possible notable advances in electric-lighting practice. Figure 3 shows the cost of producing a stated amount of light with tungsten-filament lamps for the year 1943 compared with the cost for the year 1921.[4] The entire rectangle represents the cost of light in 1921. The rectangle designated *A* represents corresponding 1943 cost. The reduction has been accomplished by advance in three elements of cost. Improved lamp efficiency (*B*) and lowered rates for energy (*C*) made the major contributions. Lowered lamp prices added considerably to the accomplishment. The combined result is that light which would have cost $10.21 in 1921, cost $2.86 in 1943.

TYPES AND SIZES

It is said that previous to the war there were some 9,000 distinctive types or sizes of lamps, including many for highly restricted applications. Approximately half of these types have been eliminated in the process of wartime conservation. Among the commonly used types so eliminated have been the 50- and 75-watt lamps and certain decorative types of lamps.

On the other hand, it is said that approximately 200 new types and sizes of incandescent lamps have been required for specialized war service. Lamp manufacturers have made a real contribution to the war effort through

1. The development of these new types of lamps as needed.*

2. Maintenance in high degree of the quality of their products despite deprivation of critical materials that to some of us might have seemed essential to the production of satisfactory-quality lamps.

In Figure 4 a cluster of charts shows for the record the approximate quantities of certain types of incandescent

* It is stated that a modern bomber plane uses about 200 electric lamps of various shapes and sizes. A battleship requires almost 30,000 lamps. A General Sherman tank (*M-4*) uses 27 lamps, and a full armored division requires about 60,000 lamps.

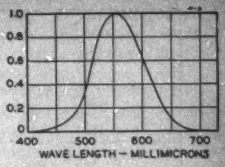

Figure 2. Relative luminosity (International Commission on Illumination standard)

lamps sold during the last prewar year, chosen for this purpose as being more representative than the subsequent wartime years. Not included in these charts, but of importance, were 48,000,000 radio-panel lamps and 256,000,000 Christmas-tree lamps.

The smallest lamp made is the so-called "grain-of-wheat" lamp, employed in surgical work. This consumes 0.17 watt and produces about one third of a lumen. The lamp itself is but 0.079 inch in diameter and 0.343 inch long. Manufacturers say that if sold by weight this lamp would cost about $7,500 a pound, because it weighs only 0.06 gram.

The largest incandescent lamp made is of 50,000 watts. It has a bulb 20 inches in diameter and weighs about 35 pounds. It produces 1,600,000 lumens or about the same amount of light as 1,000 100-watt lamps. The filament alone weighs about 1.6 pounds. One has the impression that this lamp was constructed somewhat as a stunt before the war when materials were not limited. It certainly has not entered much into practical use.

The range of application of the incandescent lamp is certainly remarkable. This will be appreciated when compared, for example, with the present range of other types of light sources.

RECENT DEVELOPMENTS

"Recent" in this connection means recently before the war. Among recent developments has been the extension of the all-glass sealed-beam lamps, devised originally for automotive head-lamp purposes in the 6- to 8-volt range, to make them available for 12- to 16-volt range for trucks

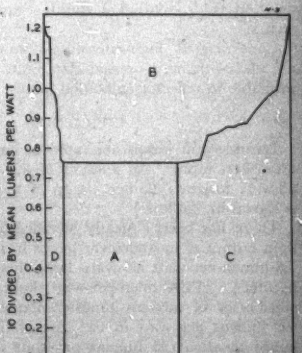

Figure 3. Lamp and energy cost of light from 60-watt specification-quality incandescent lamps (dollars per million lumen-hours)

A—Cost of light, 1943 ..... $ 2.86
Reductions since 1921
B—Through lamp efficiency increase .. 3.39
C—Through lowered rates for energy ... 3.33
D—Through lowered lamp prices ..... .63
A+B+C+D = cost in 1921 ..... $10.21

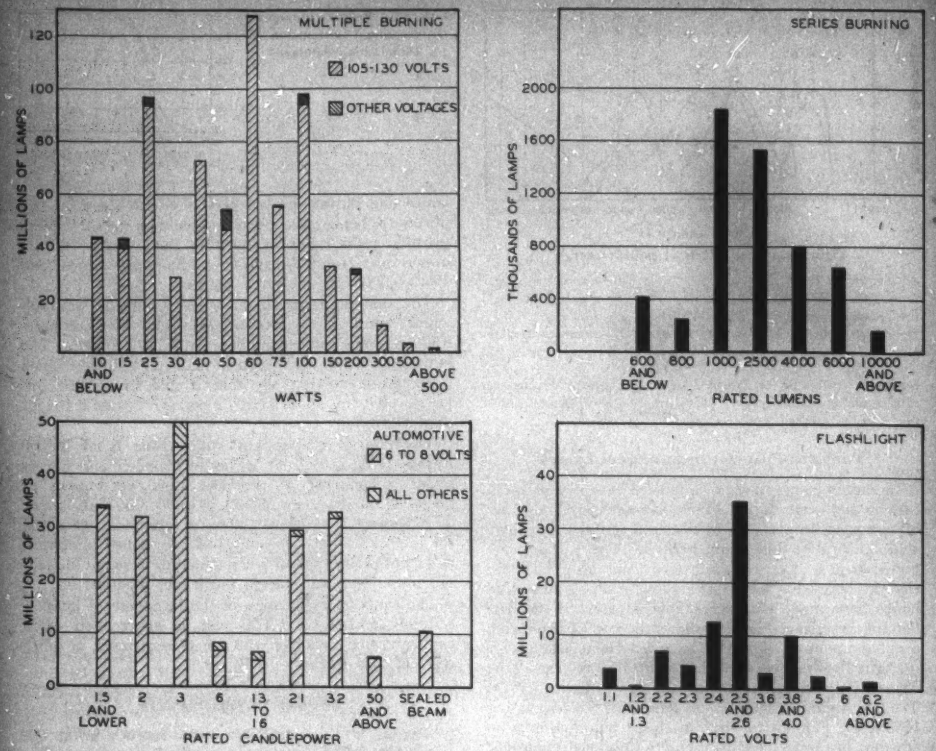

Figure 4. Quantities of certain types of tungsten-filament incandescent lamps produced in the United States in 1941

and 12- to 24-volt range for aviation work, in which sizes have gone up to as much as 600 watts. Smaller sealed-beam construction lamps were made available for aviation fields, spotlights, flashing signal lamps, and so forth.

Concentrated high-intensity illumination for indoor use and with hard pressed-glass bulb for outdoor use is available in reflector-embodied lamps.

EFFICIENCY

Incandescent lamps are rated in terms of lumens per total watt input. An analysis of the energy input to a 60-watt tungsten-filament lamp of modern construction is shown in Table I.[5]

There has been a steady advance in the efficiency of light output of incandescent lamps in recent years. The 7.8-lumen-per-watt 60-watt lamp first introduced had become a 13.9-lumen-per-watt lamp. The range of efficiencies of modern tungsten-filament lamps is from 4.5 lumens per watt in the case of three-watt 120-volt lamps to about 36 lumens per watt in the case of the short-life photoflood lamps. Among lamps generally employed for illumination purposes the range is approximately 9 to 21 lumens per watt. It is probably a fair estimate that incandescent electric lighting is accomplished with a light-production efficiency of about 13 lumens per watt. This is comparable to about 40 lumens per watt for fluorescent lamps. Maximum efficiency of solar radiation has been estimated at approximately 86 lumens per watt, corresponding to black-body radiation at 6,500 degrees Kelvin.[6]

PERFORMANCE

The characteristic performance of specification-quality lamps* of the usual residence-lighting types is shown in Figure 5. The 60-watt lamp, the most widely used size, declines about ten per cent in lumens to the end of its 1,000-hour life and about seven per cent in efficiency. Rated lives of other lamps range from 2 hours for photoflood lamps to 3,000 hours in the case of some types in which replacement is difficult. The life of incandescent lamps, of course, depends upon the filament temperature, varying inversely as about the seventh power of the lumens per watt. For lamps entering into general lighting service, conventional rated lives are 1,000 and 750 hours for residence types, 750 hours for larger commercial lamps, 1,500 hours for sign lamps, and 3,000 hours for group-replacement street series lamps.

* Specification-quality lamps are products which have been made to comply with the requirements of the Federal Specifications for Incandescent Lamps.

The simplicity, interchangeability, and convenience of application that characterize incandescent lamps have led to a great variety of applications in which it has been practicable to embody most of the advances of illuminating-engineering knowledge with regard to such qualities as direction of dominant components of light, degrees of diffusion of light, intensities of light, and limitations of brightness of exposed sources. The result has been excellent advance in electric-lighting practice.

The convenience and flexibility of the incandescent lamp are illustrated in the two-filament three-light type which has attained such large popularity in portable equipment in residence lighting.

Among disadvantages of the incandescent lamp are sensitiveness to voltage fluctuations (a 5 per cent decrease in volts causes a 15 per cent reduction in light output); the production of an undesirable amount of heat incident to the lighting process; and the relatively low efficiency of light production—low in comparison with some light sources, but high in comparison with lamps of a few years ago.

Favorable qualities of incandescent lamps include practically instantaneous starting (accompanied, however, by a large short-time inrush of current to the cold filament); filament thermal lag that reduces cyclic flicker in a-c service to an extent that makes it practically inappreciable under ordinary conditions above 40 cycles per second; and close approximation to unity power factor. The ready facility with which filament lamps of different sizes may be substituted for each other must count also as an advantage for incandescent lamps. An attractive feature of incandescent lighting is the agreeable color of the light. Humans have evolved under sunlight and firelight. The daylight period has been the occasion for all kinds of activities; the firelight period is associated with comfort, safety, repose. The two form extremes of radiation that approximate black-body character. Incandescent electric lamps confront the human mind and the human eye with a light color quality that is agreeable.

INFRARED LAMPS

The radiation from 7,800 to 20,000 angstroms is sometimes called the "near infrared." The region beyond 20,000 is called the "far infrared." Glass is practically opaque to radiation of longer wave lengths than 40,000. Glass filters having high transmission in the infrared and high absorption in the visible have been developed. Filaments in drying lamps are operated usually at about 2,500 degrees Kelvin.[7] Such filament lamps have been used successfully for radiant-energy drying in baking, heating, and evaporating moisture, and for softening, expanding, or treating materials. Sealed drying lamps of 500- and 1,000-watt sizes are equipped with cover glass of the kind mentioned.

Tungsten incandescent lamps have peaks in the infrared as shown in Table II. Wave lengths of the order of 10,000 to 12,000 angstroms produce maximum penetration of aqueous bodies. Lamps provide peak penetration at about 11,000 angstroms.

The use of radiant energy from drying lamps[8] offers opportunity for conserving space and for effecting economies with increased production in numerous industrial drying operations. In manufacturers' catalogues drying lamps are listed in variety that appears to be quite adequate to all demands. Technical information regarding their use is supplied in readily usable form. In the application of these lamps there is opportunity for engineering ingenuity. Since the materials and the engineering ability are available, this application of light sources rapidly is assuming great importance.[9,10] Manufacturers' literature on the subject features, not without reason, such expressions as "The modern way to bake, dehydrate, or dry"; "faster, cheaper, and easier drying, baking, and heating."

Mercury-Vapor Lamps

The mercury-vapor arc lamp is a remarkably versatile device. Its characteristic radiation lines vary in intensity with temperature and pressure throughout a wide range. The ultraviolet spectrum lies between 4,000 and 1,000 angstroms.[11] Ultraviolet energy from the sun reaches the earth's surface down to wave lengths 2,900 to 2,800 angstroms. The mercury-vapor lamp can be made

Table I. Energy Input to Modern 60-Watt Tungsten-Filament Lamp

	Per Cent
Rated visible spectrum	7.5
Gas loss—heat convection and conduction	13.5
End loss—conduction by leads and support wires	1.2
Filament radiation (an additional 6 per cent bulb and base heat absorption is involved)	80.8

Table II. Wave Length of Peak Radiation of Tungsten Incandescent Lamps

Color Temperature (Degrees Kelvin)	Angstroms
2,150	12,000
2,800	10,000
3,300	8,000

Table III. Mercury-Vapor Lamps Produced in 1942

Watts Per Lamp	Thousands of Lamps Per Year
Bactericidal Lamps	
4	3
5	10
15	24
30	2
Sun Lamps	
100	11
130	5
275	12
400	18
Various	5
For Illumination Purposes	
Type *H*	
100	15
250	21
400	127
1,000	3
Cooper-Hewitt	
All sizes	53

This table does not include high-power therapeutic radiators for use under medical direction and in certain industrial processes, of which it is understood that more than 5,000 were sold in 1942.

Table IV. Light-Producing Efficiencies of Principal Type-H Lamps

Lamp Watts	Rated Initial Lumens Per Watt	Lumens Per Watt at 70 Per Cent Rated Life
100	35	30
250	30	25
400	40	35
3,000	40	

Table V. Spectral Characteristics of Some Mercury Lamps

Watts	Relative Ultraviolet (Below 5,800 Angstroms)	4,358 Angstroms (Blue)		5,461 Angstroms (Green)		5,780 Angstroms (Yellow)		Continuous (Visible)		Relative Infrared (7,600–26,000 Angstroms)
		Lumens	Per Cent	Lumens	Per Cent	Lumens	Per Cent	Lumens	Per Cent	
H-1 . . 400	2.1	110	0.7	7,860	49.1	6,800	42.5	1,230	7.7	40.9
H-2 . . 250	1.2	55	0.7	3,770	50.3	3,245	43.3	430	5.7	14.6
H-4 . . 100	1.6	25	0.7	1,755	49.6	1,255	35.9	485	13.8	14.7
H-5 . . 250	4.6	70	0.7	4,630	46.3	4,040	40.4	1,260	12.6	32

to radiate within this region, and also in considerably shorter wave lengths and in longer wave lengths.

Radiation in the region 4,000 to 3,200 angstroms is most useful for photochemical effects. That between 3,000 and 2,400 angstroms is valuable for activation of vitamin *D* in sterols. The region below 2,800 angstroms is most effective in destroying microorganisms. All of these purposes are served by mercury-vapor lamps. The low-pressure lamps, with strong radiation in the 2,537-angstrom line are of value for bactericidal purposes. The sun lamps, with strong radiation at 2,967 angstroms, are effective for erythemal, tanning, and antirachitic purposes. Both low- and high-pressure lamps have usefulness in the photochemical and industrial-illumination fields. The very high-pressure water-cooled lamp is a concentrated source of light, valuable for projection purposes. Certain smaller mercury-vapor projection lamps have a variety of applications, including bactericide and theater lighting.

A mercury arc in a glass tube produces illumination. Line that tube with phosphors, and it becomes a fluorescent lamp. Replace the tube with fused quartz or ultraviolet transmitting glass, and it becomes an ultraviolet radiator. Yet it is the same kind of mercury arc!

Quantities Produced. The approximate quantities of certain types of mercury-vapor lamps produced during 1942, as reported by principal manufacturers are shown in Table III.

FOR ILLUMINATION PURPOSES

Light-producing efficiencies of the principal type-*H* lamps are listed in Table IV. These lamps require some few minutes for starting and, if the circuit is interrupted, will not restart immediately. They are, of course, suitable primarily for use in industrial installations. They are often used in connection with incandescent lamps of high wattage to produce better color value and to insure against full outage. Abroad, especially in England, these lamps have been used chiefly for street lighting. In cities they were thought to complement show-window lighting nicely, while in suburbs they illuminated the green foliage pleasingly.

Color. The color of mercury arcs is so largely subjective that attempts to compare it with daylight are complicated. Buttolph[15] makes graphic comparison of an incandescent lamp, a sodium lamp, the Cooper-Hewitt lamp, and a high-intensity mercury lamp, by assigning to the spectral lines widths such that their areas are proportional to their relative intensities, and the total line areas represent the visible energy necessary to produce equal luminosities. Trichromatic sensations are hardly applicable in the case of these line-spectra sources. However, in the high-pressure mercury lamps there is shift away from shorter- to longer-wave-length energy, and a continuous background appears in the spectrum, with betterment of color quality for most illuminating purposes. Some spectral qualities of certain high-pressure mercury lamps are cited in Table V.[31]

ACTIVATION OF FLUORESCENT MATERIALS

The high-pressure mercury-vapor lamps that are catalogued as *H*-3, *H*-4, and *H*-5 are of high efficiency and, producing 3,660 angstroms radiation, are useful for activation of fluorescent materials used in theatrical and decorative work. They are useful too in many photoprinting applications that are dependent upon high intensity of near ultraviolet. The *H*-3 lamp is being used in printing the sound track on films. The *H*-4 lamp in a reflector red–purple bulb is much used for exciting fluorescence.

A phosphor designated 360 *B-L* is utilized in mercury-vapor lamps ranging from 3 to 40 watts. It converts the 2,537 mercury radiation to energy radiated between 3,000 and 4,200 angstroms with relatively little radiation in the visible spectrum. The 2,537 radiation is substantially suppressed. This lamp is useful for activating fluorescent materials and in certain photochemical processes. A four-watt d-c lamp of the type just mentioned is used for illuminating airplane instrument panels.

HIGH-PRESSURE QUARTZ MERCURY-ARC LAMPS

Ultraviolet radiation from these sources is relatively greater than in the low-pressure lamps, though the line of greatest radiation may not be so well adapted for some purposes while being better adapted for others. These lamps, operating at from 10 to 100 atmospheres with quartz inner bulb, have spectra that approach the continuous with a line spectrum superimposed. The 1,000-watt water-cooled lamp produces about 65,000 lumens initially at 65 lumens per watt or, if the auxiliary be taken into account, at about 54 lumens per watt. It is employed in the laboratory, having a life of only about 50 hours.

High-pressure quartz mercury arcs are used in various photochemical works. They are a preferred source for irradiating milk and other foodstuffs. They are employed in the synthesis of rubber and the curing of enamel coatings and patent leather, and find wide application in tests of fastness of dyes, purity of paints, and aging of fabrics. Such sources are used also in blueprint machines, in photo-

Table VI. Results of Experiments With Hot-Cathode Germicidal Lamps

In a 4,000-Cubic-Foot Room

Watts Per Lamp	Equivalent to Air Changes Per Hour
30	100
15	45
8	40
4	10

Table VII. Typical Phosphors Used in Fluorescent Lamps

Phosphor	General Color	Exciting Range* (Angstroms)	Sensitivity Peak (Angstroms)	Emitted Range (Angstroms)	Emitted Peak (Angstroms)
Calcium tungstate	Blue	2,200–3,000	2,720	3,800–7,000	4,400
Magnesium tungstate	Blue–white	2,200–3,200	2,850	3,800–7,200	4,800
Zinc silicate	Green	2,200–2,960	2,537	4,500–6,200	5,250
Zinc beryllium silicate	Yellow–white	2,200–3,000	2,537	4,500–7,200	5,950
Cadmium silicate	Yellow–pink	2,200–3,200	2,400	4,300–7,200	5,950
Cadmium borate	Pink	2,200–3,600	2,500	4,000–7,200	6,150
360 *BL* phosphor‡	Blue ultra	2,200–3,200		3,200–4,600	3,600

* 2,200 angstroms is lower limit of measurements.

‡ Used for exciting fluorescent chemicals, blueprinting, and so forth.

printing apparatus, in the activation of vitamin *D* in foodstuffs and in pharmaceutical preparations.

Sunlamp. Luckiesh[13] in "Artificial Sunlight" states that in summer on a clear day at noon erythemal energy is received at the earth's surface at about equal parts from the sun and from the total sky. At other times the ultraviolet from the sky exceeds that from the sun. Sunlight spectra extend down to about 2,900 angstroms. Porter[14] describes sun lamps in terms of erythemal power with spectral curves. The most powerful wave length in producing erythema is at 2,967 angstroms. The erythemal effectiveness curve from 2,800 to 3,180 angstroms is shown.

There are five sun lamps having different radiation characteristics with the *S2* lamp producing about one third of the ultraviolet that is produced by the others. Irradiation of the body is one way to produce vitamin *D*. Coblentz[15] notes that radiation of 2,540 angstroms does not penetrate deeply into the skin. Erythemal effects are superficial. On the other hand, radiation of 3,100 and longer beyond erythemal dosage does penetrate and may produce a blister. In addition to application to the human body, experiments in irradiating farm animals and poultry have produced successful results, as, for instance, in increased production and hatchability of eggs.[16] These lamps offer an alternative method of prevention and cure of rickets.

BACTERICIDAL LAMPS

Within the ultraviolet range the region 3,000 to 2,000 angstroms is considered to have germicidal value.* Bactericidal action is said to be at a maximum at approximately 2,660 angstroms, decreasing for shorter and longer wave lengths, but rising again for radiation below 2,375 angstroms. This is for the generality of pathogenic bacteria concerning which some information is available. There are known exceptions.

Within this bactericidal range the 2,537-angstrom resonance line of mercury is excellently placed for effectiveness. About half the radiation from low-pressure mercury-arc lamps is in this 2,537-angstrom band. These lamps, equipped with ultraviolet transmitting glass, therefore are an efficient and economical source of bactericidal radiations. They are available in two types as follows:

Cold cathode, known to the trade as "Sterilamp," is rated at 15 watts. It starts at about 575 volts and operates at about two-thirds that value.

Hot cathode, known to the trade as "germicidal lamps," are available in 30-, 15-, 8-, and 4-watt sizes. Except for the absence of phosphors and the use of ultraviolet transmitting glass, they are similar to fluorescent lamps. These lamps decline in efficiency with low temperatures. At freezing, the output is 60 per cent; at 0 degrees Fahrenheit it is 30 per cent of normal.

Certain infections, including common colds, are believed to be carried by air-borne bacteria or virus. Energy radiated in the stated regions offers a practicable means of killing such bacteria. Installed in ventilating ducts, where that is feasible, or so placed as to irradiate the upper stratum of air in a room where there is fair circulation, these ultraviolet radiators offer means of purification of the air that is analogous to the purification of drinking water.

Experiments as to the lethal effectiveness of such ultraviolet radiation have been made principally with bacilli coli, a rather harmless organism having characteristics thought to be similar to those of many pathogenic bacteria. Working with these bacilli coli, experimenters have reported achievement by these means of an equivalent of air replacement of 4,000 cubic feet per minute per person, which is 10 to 15 times the actual air replacement needed to keep carbon dioxide down to a satisfactory level. It has been reported further that one of these ultraviolet radiators in an average-sized duct will kill over 90 per cent of the bacteria in the air passing through the duct at a rate of 500 to 600 cubic feet per minute.[17]

A single such radiator irradiating the upper part of an average-sized office is said to be capable of reducing the bacteria count as much as could be accomplished by opening all of the windows on a breezy day. Other reports are that one small ultraviolet lamp irradiating about 3,000 cubic feet of air has a sanitary effect equivalent to 50 or 100 air changes per hour.[18]

Irradiation of the upper stratum of the air in a room for bactericidal purposes is sometimes referred to as "sanitary ventilation."* The effectiveness of such methods is lower when humidity is higher.

In certain experiments with hot-cathode germicidal lamps the results shown in Table VI have been observed.[19] There seems to be no doubt that under properly controlled conditions such ultraviolet radiation is effective in killing air-borne microorganisms and may be used to supplement other measures for the prevention of cross infection. Experiments thus far are promising and indicate the possibility of a large and useful application in the near future. In places where there is illness or where there are large assemblages of people the applicability seems immediately indicated. Hospitals, schools, theaters, passenger carriers, and the like might benefit. Since it has been estimated that an average of 400,000,000 colds a year cost the nation half a billion dollars, the prospect of being able to reduce infection through air purification is very attractive.

It is interesting to contemplate the value that these

* Mayer[11] notes that germicidal effects differ with different bacteria. 3,100 angstroms is a lethal radiation wave length for some, but action in other cases has been observed at 2,250 angstroms.

* A popular article describing successful results of experiments in preventing cross infections in cases of measles and colds appeared in the *New Republic* for December 15, 1941, under the authorship of Bruce Bliven. It was condensed in the *Readers' Digest* for January 1942.

bactericidal lamps may possess for occupants of heated submarines and heated cabins of stratosphere airplanes. Regions inhabited by mermaids and gremlins may be provided with California climate!

Sterilization. Ultraviolet radiators are entering into use in hospital operating rooms for prevention of cross infection and of infection in wounds. It is said that a six-to-one reduction in the incidence of wound infections in certain types of operations has been shown in records of two hospitals. Such lamps for use in operating rooms, nurseries, and hospital wards, where they are used under medical supervision, are listed by the American Medical Association as "Accepted." However, sources radiating appreciable energy of wave lengths shorter than 2,800 angstroms are not recommended for use by laymen for therapeutic purposes.

Smallest of the ultraviolet lamps is an arc in a quartz tube within a container that is about $10^1/_2$ by 3 inches. These are provided for treatment of slow-healing wounds, abscesses, ulcers, and so forth.

Miscellaneous Applications. Sanitizing uses to which ultraviolet radiators are being applied include:

Meat storage places	Sterilizing special canners' sugar
Restaurants	Hospital bathrooms
Bakeries	Industrial washrooms

Water sterilization

Conservative Application. In the realm of prophylactic and therapeutic practice, as well as in the field of health generally, a great deal of conservatism is required from engineers. A suggestion as to health benefits attributable to ultraviolet radiation is likely to give rise to ill-founded and extravagant commercial claims by irresponsible people. Much of the experimentation in this field has been carried on by commercial interests that are desirous of selling equipment for this purpose. Engineers know leaders in this experimental field and respect them. Others, however, may draw from their work far-reaching conclusions that are hardly justified. It would appear that there is a need for more independent disinterested experimentation in ultraviolet applications for prophylactic and therapeutic purposes. Indications point to an important and growing field of usefulness for these sources of radiation. It is important that it be developed conservatively. Ultraviolet radiators are no panacea for either prevention or cure. They are useful devices that may be expected to fill an increasingly important place in the future.

Sodium-Vapor Lamps

Unlike other lamps, the sodium lamp[30,31] is not at all versatile. No matter how it is treated, it sturdily insists upon radiating its light at 5,893 angstroms. Before the war these lamps were being sold at a rate of about 11,000 a year. They are used for highway lighting and lighting of traffic intersections where a different effect is sought in order to keep motorists alert. They have also been used for lighting railway yards and airfields. The monochromatic light should have value wherever high visual acuity is involved and where the color characteristic is unobjectionable. Since the radiation is at a wave length close to that of maximum eye response, the sodium lamp is a highly efficient illuminant, the 10,000-lumen lamp producing light at about 50 lumens per watt with auxiliary loss included.

Fluorescent Lamps

The genealogy of the fluorescent lamp traces back to the Cooper-Hewitt mercury-arc lamp[32] and the Claude neon tube.[33] Electrically it is an arc discharge through a low-pressure atmosphere of mercury vapor and rare gases. The literature of the art records the distinguished development of the mercury-arc lamp into regions of higher and higher temperatures and pressures with expanding fields of usefulness. It records also the advances in sign lighting, including the employment of gases or vapors other than neon, to produce the ingenious colorful outdoor displays with which we in America are most familiar. In the last few years these two illuminants, while continuing to serve with increasing effectiveness in their distinctive fields, have been developed through the addition of fluorescent materials, called phosphors, to afford valuable service in the field of general illumination.

As a result there are now mercury-vapor lamps from which but little of the light produced in the characteristic mercury-radiation lines of the visual spectrum emerges, but from which a relatively large amount of light is radiated from the fluorescent materials that are activated by the ultraviolet energy of the mercury arc.

Ballasts. To stabilize the arc some form of ballast is required. Probably the simplest form of ballast is the series resistance, as now used in d-c service, but, because of its energy consumption and consequent reduction in operating efficiency, this arrangement finds little use. The most commonly used ballast is an inductive reactance, obtained either directly in the form of an iron-core choke or indirectly through a high-leakage transformer. Both of these arrangements unless modified give operating circuits of low power factor.

Starting. Two methods currently are employed for striking the arc:

(*a*). To provide a special initial ionization of the arc stream.

(*b*). To apply an initial voltage higher than operating voltage.

The first was developed in mercury-vapor-lamp practice; the second in operation of gaseous-discharge electric-sign tubes.

Superior Efficiency. The greatest advantage of fluorescent lamps over the generally used incandescent lamps is the production of two or three times as much light for the same expenditure of watts with less accompanying heat. This makes practicable the attainment of the higher levels of illumination that production efficiency demands where efforts are dependent upon visual ease. And this important objective can be attained without overburdening existing wiring systems or with lesser wiring costs in new systems. Furthermore it makes available an abundance of light without undue elevation of ambient temperatures and without handicapping air-conditioning systems.

Output Maintenance. All fluorescent lamps containing mercury depreciate in light output as they operate. The rate of depreciation varies for tubes of a given diameter with the current density and other factors.

COLOR OF LIGHT

Synthetic fluorescent materials have been developed to produce light of a great variety of colors. These are mixed as desired. The generally reported phosphors as commonly used in fluorescent lamps are listed in Table VII.[34]

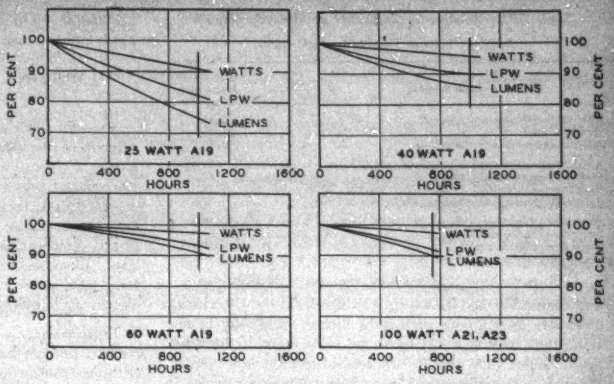

Figure 5. Performance characteristics of specification-quality tungsten-filament incandescent lamps

The most largely used fluorescent lamps are of the types designated "white" and "daylight," respectively. The white lamp produces light of a color that has found wide acceptance in industrial and commercial installations. It blends well with natural light. Because of the one-tenth elemental mercury radiation, it has a barely perceptible yellow–green cast that renders it unsuitable for some color-critical purposes. The light of the daylight lamp, second in popularity, has a similar characteristic but is stronger in the blue and less acceptable for use in places of assemblage.

A fundamental difference between light of fluorescent lamps and either daylight or light of incandescent lamps is the presence in the former of the spectral lines of the normal mercury discharge and a deficiency in the deep red.[26]

The color difference is somewhat difficult to depict. In Figure 6 a comparison is made between spectrophotometric curves of

3,500-degree-Kelvin black-body radiator[38]
300-watt tungsten-filament lamp (2,905 degrees Kelvin)[37]
3,500-degree-Kelvin fluorescent lamp[26]
Noon sunlight[39]

The mercury-line radiation is superimposed upon the continuous spectrum of the light from the phosphors. The vertical bars around lines representing, respectively, wave lengths 4,047, 4,358, 5,461 and 5,780 angstroms are adjusted so that the enclosed area upon the spectral curve indicates the magnitude of the energy radiated in these respective lines. Light of day and that from incandescent sources lie close to the locus of black-body radiation. The light from fluorescent sources has distinctive characteristics. The effect of the yellow–green mercury lines is to exalt the brilliance of corresponding yellow and green pigments to a degree that is not experienced in other light of equivalent synthetic ocular value. Red pigments generally are dull under fluorescent light.

A so-called "soft-white" lamp, designed to provide more acceptable appearance of meats, foods, complexions, and so forth, was made prior to the war but has been eliminated as a part of war curtailment. Its light contained more of the orange and light red elements and emphasized less the yellow–green colors. At a loss of about 25 per cent in efficiency there was achieved a color of light that for many purposes was pleasing. When its manufacture will become practicable again, something of the kind may be expected to be placed on the market.

Such information as is available indicates that there is no material change in the color of light from fluorescent lamps throughout their operating life.

Cyclic Flicker. In lamps that operate on 60-cycle current, the arc is extinguished 120 times a second. The visible radiation from the phosphor that produces blue light varies almost instantly with the change in activation. The light from other phosphors lags a bit but follows the variations in activating energy very largely. The result, on alternating current, is a pronounced cyclic flicker of light modified by a slight color flicker. On 60-cycle circuits the relative cyclic flicker expressed in per cent deviation from mean light output has been found to be

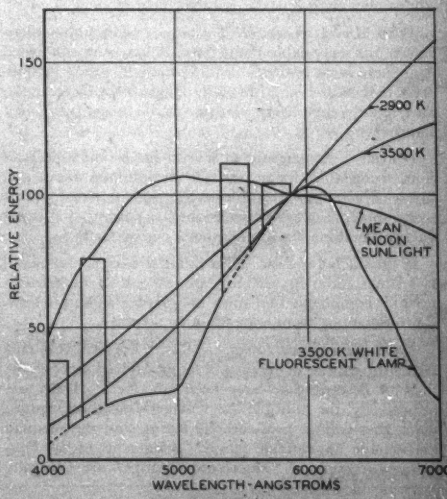

Figure 6. Comparative spectral distributions

Table VIII. Relative Cyclic Flicker on 60-Cycle Circuits

Per Cent Deviation From Mean Light Output

Light Source	Relative Cyclic Fluctuation
100-watt tungsten-filament lamp	5
Red fluorescent lamp	10
40-watt tungsten-filament lamp	13
2 white fluorescent lamps on phase-offsetting auxiliary	16
Green or pink fluorescent lamp	20
Gold fluorescent lamp	25
2 daylight fluorescent lamps on phase-offsetting auxiliary	25
Single white fluorescent lamp	35
Single daylight fluorescent lamp	55
Single blue fluorescent lamp	90

approximately as shown in Table VIII.[23] Uncritical observers may ignore such light flicker, especially in installations in which the need for refinement in lighting results is not very urgent. In critical service, however, it requires to be modified to lessen its stroboscopic effects.

The cyclic light flicker may be reduced to an unobjectionable level where several lamps are used to illuminate the same area if, polyphase service being available, the several lamps are connected to different phases, thus offsetting the maximum–minimum extremes of light production.* This arrangement, however, leaves the power factor unsatisfactorily below unity and in need of correction.

Brightness. The brightness of white and daylight fluorescent lamps is close to the acceptable limit of exposure in the field of view. It is so close indeed that in the industrial installations where ceilings are of good light reflectance and the fluorescent lamps are mounted high and cover a large part of the ceiling area, some think it acceptable to operate the lamps unshielded. It is the consensus of opinion, however, that in other installations the lamps should be shielded to reduce their brightness to acceptable values. This becomes especially important where exacting visual tasks are performed and where the lamps may enter into the ordinary field of view.

Vision Under Fluorescent Lighting. Through experiments and reasonable deductions, it has been concluded that there is no appreciable difference in vision attributable to the differences in quality of light from, respectively, "daylight" fluorescent lamps and tungsten-filament lamps.[20]

Design. Apparently in several important aspects of fluorescent lamp design, there is an optimum above and below which less favorable results are obtained. This seems to apply to tube dimensions, arc current, activating energy, combination of phosphors, and so forth.

In Critical Installations. Humming noises from auxiliaries and radio interference are aspects of fluorescent-lighting equipment that must be guarded against in critical installations, as in home-lighting service.

Types of Fluorescent Lamps. There are available currently three forms of fluorescent lamps evolved through the lines of descent that have been described. They are, respectively, the multiple low-voltage hot-cathode lamps; the higher-voltage cold-cathode lamps, and the rectified low-voltage hot-cathode lamps. Statements in the foregoing discussion of "Fluorescent Lamps" are generally applicable. On the following pages are comments that apply only to one or another of the types.

* For other means of obviating objectionable flicker, see discussion under multiple low-voltage hot-cathode lamps.

MULTIPLE LOW-VOLTAGE HOT-CATHODE FLUORESCENT LAMPS

Some of the electrical features of these lamps are considered in the discussion of mercury-vapor lamps. The range of these fluorescent lamps for general illumination purposes at present is from 15 to 100 watts. The 15- to 40-watt sizes, inclusive, fit standard lamp holders. The larger-size lamps fit into Mogul lamp holders. These lamps, however, are not generally interchangeable as to size. Because of different lengths, spacings between lamp holders are different. There also are four-, six-, and eight-watt lamps that fit into miniature lamp holders.

Transformers. The 15- and 20-watt lamps that do not require higher than line volts for starting are operated without transformers. The 30- and 40-watt lamps, requiring a minimum of 200 volts open circuit for dependable starting, are provided with transformers for operation on 120-volt circuits. They may be operated without transformers on the 208-volt supply lines that commonly are available in both industrial and commercial installations. The 100-watt lamp is sometimes operated without transformers, the lamps being connected two in series and operated with proper ballasts from a 265-volt source that is available in many industrial installations. (Phase voltage corresponds to a 460-volt four-wire three-phase supply.) Special four-lamp ballasts are available for this application.

Ballasts. Growing out of practice in the operation of high-intensity mercury lamps[21] has come the operation of a pair of lamps on a ballast in which a capacitor is used to provide a lead current for one lamp that is out of phase with the lagging current of the other lamp. A compensator is placed in this lead lamp circuit to insure adequate preheating of the electrodes. Such operation insures both satisfactory power factor and adequate reduction of the magnitude of light flicker. From the better power factor come reduced wiring costs and advantage for generating and distributing equipment. From the reduced light flicker come diminished stroboscopic effects that otherwise would be objectionable in critical installations. This type of corrected auxiliary is very generally used.

The four-lamp ballast for 100-watt lamps previously mentioned accomplishes similar power-factor and light-flicker corrections. It achieves a small gain in lumens per watt of the lamp and its equipment.

Flicker Correction. In discussion of fluorescent lamps in general, the magnitude of cyclic fluctuations of the light of fluorescent lamps was compared with that of incandescent lamps. The advantage in light-flicker reduction accomplished through the use of twin lamp ballasts is shown in Table VIII.

Starters. A starter in the circuit of each lamp delays for a few seconds the application of voltage while the electrodes are being preheated. This delayed start is not necessary but is provided in the interest of good performance of the lamp. Failure of the lamp usually occurs through decline of the emissivity of the electrode. The rate of this decline is greatly affected by the number and frequency of starts. In the laboratory with one start every three hours, a life of well over 3,000 hours is obtained. A starterless ballast is practicable but in the present stage of

development is not advisable because of impairment of lamp life.

Because the starting current is about double the operating current, the ballast of fluorescent lamps will become overheated if a deactivated lamp is permitted to remain in the circuit. To obviate possible difficulties, a type of starter recently put into production includes a thermal switch in series with the starter timing switch. When the fluorescent lamp fails and the starter makes a few attempts to establish the arc, the resultant heat opens the thermal switch which remains open until the failed lamp is replaced. This eliminates the flow of current through the lamp auxiliary, reducing the watts dissipated at the transformer. An extinguished lamp seems a more acceptable signal for replacement than does a blinking lamp. And the likelihood of damage through elevated temperature in the ballast is eliminated. These "no-blink" starters are now available for 40- and 100-watt lamps. They are available in both the automatic and the manual reset type.

Efficiency. The optimum operating temperature for hot-cathode fluorescent lamps is an ambient of the 100 to 120 degrees Fahrenheit range. Above and below this range the output and the efficiency fall off. Only 25 to 35 per cent of the total energy dissipated is radiated from fluorescent lamps in the infrared region. Amick[34] analyzes the 40-watt input as given in Table IX.

It is evident that in comparison with the gas-filled tungsten lamps, in which 60 to 75 per cent of the energy is radiated in the infrared region, the light from fluorescent lamps is relatively cool light. According to this analysis, about 18.5 per cent of the applied watts is converted in these fluorescent lamps into light within the visible spectrum.

The rating of these lamps as to light-output efficiency is customarily based upon the watts delivered to the lamp, exclusive of that absorbed in the auxiliaries, which for two lamps on a "tulamp" ballast is about 17 watts. This form of rating is used presumably because the watts dissipated in the auxiliaries depend upon the type of auxiliary used. On this basis the 40-watt white lamp, after the decline of its initial 100-hour period, produces approximately 52 lumens per watt. The manufacturers seem to feel that a ten per cent increase is probable in this efficiency of light production. The depreciation in efficiency at 70 per cent of rated life is about 15 per cent. This the manufacturers believe that they are on the way to improving quite appreciably, perhaps cutting the rate of decline almost in half.

These fluorescent lamps are quite sensitive to changes in temperature of ambient. For specimen lamps of several sizes ranging from 15 to 100 watts as produced in 1941, the variations under reasonable test conditions are as shown in Figure 8. Within the usual range of indoor temperatures, say 50 to 90 degrees Fahrenheit, variations in efficiency are not more than five per cent.

The sensitiveness of these lamps in this respect is a nightmare to photometrists who seek reproducibility of test results. With temperature and other conditions well-controlled in a laboratory, variability due to changes in the ambient temperature is minimized in the case of bare lamps. When, however, these lamps are used in any kind of housing or in a reflector, the temperature of the enclosure. In such case it is important to be sure that the lamp is operated in the same position as that in which it will be used and to make photometric measurements without alteration of that position.

Use of the hot-cathode fluorescent lamps outdoors in cold weather is inadvisable unless special precautions are taken to avoid starting troubles.

Applications. The use of fluorescent lighting was growing by leaps and bounds until the war put an end to its development except for Government and war-production purposes. In the last two years new installations have been limited chiefly to such uses. Most recent experience therefore has been in industrial and Government office-building lighting. When materials and manufacturing facilities are released from war service, it is probable that the rapid increase of prewar months will be resumed and accelerated in industrial and commercial lighting fields.

Many people also are looking for extensive development of fluorescent lighting in residences. In the utility rooms of the home, as the kitchen and laundry, fluorescent lamps may be expected to find ready application. It seems apparent that in new or reconstructed buildings long slender sources can be embodied architecturally to secure effects that may be wanted in some cases. High voltages, however, are to be avoided. When portable lamps and attached lighting fixtures are considered, the large physical dimensions of the fluorescent lamps required to secure adequate light flux seem likely to intrude as a difficulty. Small sources that lend themselves to dainty and graceful structures for small rooms are desirable. Circular fluorescent lamps that may become available will approach this objective, but it will be difficult to get enough light from them to provide general illumination.

In case these difficulties are overcome, there still will remain the question as to the desirability in most cases of trying to substitute fluorescent for incandescent lamps in the home. If the fluorescent-lighting equipment is to be well done and to serve for satisfactory lighting, it seems likely to be more costly than incandescent lighting. It will be more complicated, and the acceptability of the color of fluorescent light remains to be established. Doubtless when the war is over, light of color that will be more pleasing for residence use than is the present "white" lamp will be made available. Perhaps the former "soft white" will be restored. So long, however, as the radiation in the characteristic mercury lines produces something like ten per cent of the total illumination, the acceptability of fluorescent light for other than utilitarian rooms of the home may be questioned.

Prospect as to Types of Fluorescent Lamps. The trend has been toward bigger and better fluorescent lamps, but the optimum size may already have been reached. As with illuminants in general, economical lighting is achieved through standardization upon a few types that can be produced in large quantities. As always, there is a demand

Table IX. Analysis of 40-Watt Input of Hot-Cathode Fluorescent Lamps

	Conversion of Energy Within the Lamp (Watts)	Ultimate Conversio (Watts)
Light	0.9	7.4
Ultraviolet radiation (55 per cent at 2,537 angstroms)	2.2	
Heat	17.1	Radiated 10.9 Convected and conducted 21.7

for specialty lamps to meet special requirements. As always too, something that is different can be sold merely on the ground of difference. Conspicuous among the desires that have been expressed is that for circular lamps, already mentioned. The manufacturers report that they can make such lamps when the war is over, but they apprehend that the cost will be relatively high, and the demand for them may be less than some people expect.

It might appear that the production of circular fluorescent lamps is likely to be attended with considerable difficulty. There will be questions as to the kind of ballasts and starters to be used, and as to provision for minimization of radio interference and cyclic flicker, as well as for good power factor. The type of lamp holders to be used and their location may offer some difficulty. It would seem also that the manufacturing process might be more complicated in some particulars than for straight-tube lamps. On the whole, higher cost and possibly less satisfactory performance are to be expected from circular lamps.

Cooper-Hewitt Rectified Fluorescent Lamps. In the original Cooper-Hewitt mercury-vapor lamp[32] a-c operation was accomplished by resorting to a rectifying circuit that provided a pulsating d-c discharge through the lamp. Recently this type of lamp has been equipped with phosphors for production of fluorescent light for industrial installations. There are 85-watt lamps rated at 4,000 lumens, 47 lumens per watt for the lamp alone. These lamps are available in two colors, the one called blue–white and the other called industrial white. The blue–white lamp "emphasizes the cooler end of the spectrum." The industrial white lamp gives a somewhat whiter light. A capacitor in the circuit contributes to producing a 90 per cent power factor. The maximum over-all length of the lamp is 57½ inches. The length of light source is about 52 inches. The diameter of the luminous part of the tube is 1½ inches. The lamp has a cathode and a pair of anodes. There is a flow of current through the lamp, first, for a half-cycle from one anode and then for the other half-cycle from the other anode to the cathode. Starting voltage is approximately 2½ times the normal operating voltage. There is a delay in starting for a few seconds in order to permit the cathode to attain emitting temperature. A bimetal delay element protects the lamp until the cathode attains satisfactory temperature. It is understood that manufacture of fixtures for these lamps is suspended for the duration.

HIGH VOLTAGE-COLD-CATHODE FLUORESCENT LAMPS

The high-voltage cold-cathode fluorescent lamps[33] are the immediate outgrowth of gaseous-discharge sign equipment developed in recent years as small-diameter tubes, filled first with neon and then with mercury or argon or helium to produce light of different colors for display purposes. They have been evolved out of outdoor sign-lighting practices. The availability of efficient phosphors for lining the long small-diameter tubes employed in sign work made it practicable to utilize such tubes in providing general illumination.

Electrical Features. These tubes are operated upon transformers providing secondary voltages up to 15,000, sufficient voltage being provided for striking the arc. The transformers usually are of 60- to 120-milliampere capacity. Relatively large electrodes are used, usually in the form of metal cylinders. These operate usually at about 150 degrees centigrade. The starting voltage is perhaps 1½ times the operating voltage.

There is a drop of about 130 volts per pair of electrodes operating at 100 to 120 milliamperes. The current must be kept low in order that the watts loss at electrodes may not be excessive. Yet for satisfactory efficiencies one manufacturer recommends that the 25-millimeter tubes should not operate at less than 100 milliamperes, and the 20-millimeter tubes at not less than 90 milliamperes.

As the voltage drop at the electrodes of long tubes is no greater than that of short tubes, recourse is made to long tubes and high voltages where attainment of good efficiency is sought. At a given current the voltage drop for a tube of large diameter is smaller than for a tube of smaller diameter. In the interests of efficiency the diameter of the tube is made small in order that the current per unit of cross section may approach the optimum. These relatively high voltages for starting and for operation formerly were frowned upon for indoor service. However, subject to precautionary restrictions, they are permitted in the National Electrical Code, with the result that high-voltage cold-cathode fluorescent lighting has entered quite extensively into industrial- and commercial-lighting service. Whether or not required, it would seem to be desirable to install some form of automatic circuit breaker on the primary side of the transformer to operate in case the lamp circuit be opened.

The cold-cathode high-voltage lamps start instantly without need for preheating devices.

High-voltage cold-cathode fluorescent lamps generally have been assembled in the installation, with total length of tubing adapted to the space to be illuminated. Tubes lined with fluorescent powders have been welded and assembled as required. Often there has been reliance on the ceiling as a reflector. This sometimes presents an appearance that is an improvement over that of fluorescent units having their own reflectors. But it affords less ease of cleaning and sacrifices light redirection in most cases.

These long slender tubes lend themselves readily to a wide field of custom construction. With the skill developed in sign work the manufacturers may be expected to show facility in providing a variety of shapes and sizes of tubes for special purposes, including conformity with architectural contours.

Performance. Custom assembly of tubes from various sources is subject to variables that make it difficult to arrive at typical performance statistics. There has been very little standardization of a kind that makes possible precise statements as to efficiencies. These may vary through a considerable range, being involved with extent of trans-

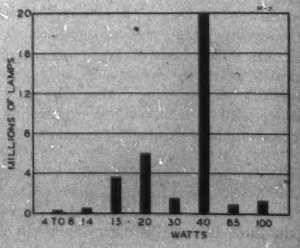

Figure 7. Hot-cathode fluorescent lamps produced in the United States in 1942

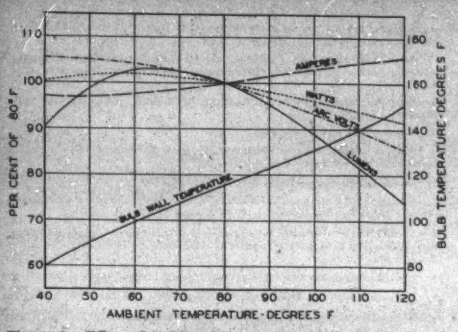

Figure 8. Effect of ambient temperature on characteristics of hot-cathode fluorescent lamps

former loss, voltage, and current. Best efficiency of light production, other things being equal, is found in longer lamps.

Among the most commented-upon installations is that of the I-T-E plant in Philadelphia, in which, after a period of operation, light was found to be produced at a rate of about 266 lumens per foot from tubes operating at about 100 milliamperes. The efficiency, including a 12,000-volt transformer loss, was about 39 lumens per watt. An average of about 35 foot-candles of illumination was produced.

Generally speaking, the brightness of these tubes is of about the same order as that of 40-watt low-voltage hot-cathode lamps. The light produced per foot is about one half, and the projected area of the smaller-diameter tubes is less.

The length of life is dependent somewhat upon the current density, but in practice has been found to be very long—several times that of the life of the low-voltage hot-cathode lamps. Whether this long life is or is not an advantage is a question. It reduces maintenance cost, but the very lack of maintenance may accelerate the rate of decline of useful light output. That decline, aside from dust obstruction, as in the case of all mercury-vapor lamps, is something to be considered. It may result after a long life in a lumen output reduced to two thirds of initial. This will raise a question of an economical "smashing point" before expiration of normal hours life.

A Standard Unit. The recently organized Fluorescent Lighting Association is engaged in standardizing cold-cathode units that can be produced in complete form in factories and shipped ready for installation. These include an eight-foot unit, the luminous part of which is about seven feet, nine inches, in length. The tubes are 20 or 25 millimeters in diameter. These standard tubes may be connected in series on one transformer with power-factor correction in any number of tubes from 2 to 12. Twelve of these 93-inch tubes will operate on a 12,000-volt transformer, the operating voltage being approximately two thirds of the striking voltage. There are other tubes being standardized of the following sizes:

84-inch, known as the seven-foot lamp
76-inch, known as the six-foot lamp
52-inch, known as the four-foot lamp

Some manufacturers are understood to be developing a system of ballast and pairs of cold-cathode lamps utilizing the same lengths of lamps as for the series arrangement, but perhaps adding an 18-millimeter tube in the 76-inch lamp.[44] These will be corrected both as to power factor and flicker. The different lengths of lamps will not differ much in light output but will differ principally in brightness.

General Considerations

ILLUMINATING ENGINEERING

After the war the engineer will have at his disposal a rich assortment of illuminants with which to contribute to the efficiency of industry and business, to the safety of traffic, to the beauty of decoration, and to the comforts of living. Abundant low-cost reliable sources offer favorable opportunity for accelerated development of the application of light. Illuminating engineering practiced as a peaceful art is one of those enterprises that offers advantage for everybody affected—the engineer, the manufacturer and distributor, the supplier of power, and, most important, the public. It is therefore a favorable circumstance that so many varied and effective sources of light are or will be available.

PROPRIETY IN REPRESENTATIONS

Some of the effects of radiant energy are not easily ascertained or measured. They are involved in recondite knowledge that is obscure to the public. The public easily may be confused as to these effects and is likely to be misled by glib representations having a pseudoscientific appearance. For instance, it is possible to represent almost any different kind of radiation that affects the visual organs as being "easier on the eyes" and to get a certain segment of the public to acquiesce in the assertion and to reassert it quite irrespective of the facts. Invisible radiation is even more incomprehensible to the public. It shares with real medicines and quack nostrums the influence of the faith curve. If it be represented to the public as a valuable prophylactic or therapeutic agent applied in certain cases of disease, some part of the public will accept the statement and feel convinced that its experience has confirmed the assertion, quite irrespective of the facts of the case.

Electric energy converted into radiant energy is rendering immense services to the public. It is likely to be more rather than less serviceable in the future. Strong representations as to its value and usefulness may be made with full propriety and with public benefit. But misrepresentations can only impede its growth in usefulness.

Those who produce light sources are among the industrialists and engineers who have had to forsake the ways of peace to put down the threat of aggressor nations against our way of life. When this menace shall be destroyed, they will turn back to the further development of light sources. Then if care is not taken, they may find the situation confused by misrepresentation in these matters that the public does not understand.

It appears to devolve upon engineers, both as an opportunity and as a duty, to do everything that is practicable to encourage valid significant representations regarding light sources in order to afford the public best practicable guidance. The engineering profession and the lighting industry ought to earn and safekeep a high degree

of public confidence in its assertions. Means should be found for discriminating between valid reasonable representations and those that mislead.

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Continuous rows of twin 40-watt fluorescent units illuminate this modern industrial plant to a level of 30 foot-candles. Mounting height is 22 feet and spacing between rows 13 1/2 feet

Enemy Army Communications Equipment

ROGER B. COLTON

Captured enemy communications equipment which has been analyzed by the Signal Corps Laboratory is described and is compared with American-made equipment in this first complete discussion of enemy signal apparatus to be made public by the Signal Corps.

AMERICAN engineers have been instrumental in giving to the United States Army and to the Signal Corps of the Army the best equipment in the world. Although engineering for civilian needs is very different from engineering for military needs, and most American engineers have spent a lifetime in civilian engineering, they have learned within a brief period of two or three years to design equipment to meet military needs and are now, in fact, military engineers.

That we now have the best communication equipment in the world is due principally to their efforts, both in the way of design and in co-operation with communication agencies of the Government. The magnitude of the task we have accomplished together is illustrated by the fact that the largest annual appropriation for the Signal Service of the Army during World War I was $83,201,000, whereas during the fiscal year ending June 30, 1943, the appropriation amounted to more than $5,500,000,000—66 times as large. Another illustration of our accomplishment lies in the fact that of the 200 principal items now being delivered to the Signal Corps, 115 were developed and standardized since July 1941. Communications have been furnished to meet the needs of the slow pace of the foot soldier and the 400-mile-per-hour speed of the Air Force pilot. These are our accomplishments.

We will turn now to the accomplishments of the enemy. The first enemy equipment to be analyzed by our engineers was the German airborne radio-communications set, *FuG* 10. The German abbreviation *FuG* means Funk Gerät, a collection of radio apparatus or, in general, what we know as a radio set. The *FuG* 10 is used in German bomber and reconnaissance aircraft, including the Junkers 88 and the Heinkel 111. The complete set consists of a long-wave transmitter and receiver, a short-wave transmitter and receiver, direction-finding equipment, intercommunication amplifiers, blind-approach equipment, and associated dynamotors and control boxes. The *FuG* 10 is capable of operation up to 1,000 miles on continuous wave with favorable conditions.

The two receivers, *EK* and *EL* are similar except for their frequencies, which are 300 to 600 kilocycles for the long-wave receiver and three to six megacycles for the short-wave receiver. The *E* stands for "Empfanger," which means "receiver," while the *K* stands for "Kurz" or "short;" that is, short-wave. (In a similar manner transmitters are designated by a large letter "*S*," standing for "sender," and "*K*," again for "short.") The circuits are both conventional superheterodynes. The standard Telefunken-type *RV*-12*P* 2,000 tube is used. *R* means tube, *V* means amplifier, 12 is the filament voltage, *P* signifies pentode, and 2,000 is the transconductance. Both receivers have four-spot frequencies that can be set by a cam-click mechanism on the main tuning condenser. The receivers are used mainly for continuous-wave or modulated-continuous-wave reception. The intermediate frequency of the long-wave receiver is 140 kilocycles, and of the short-wave receiver, 1,400 kilocycles.

The high-frequency oscillators are stabilized by means of temperature-compensating condensers. The radio-frequency and intermediate-frequency coils are all of the iron-core variety. No automatic volume control is incorporated. A test socket is available on the front panel for checking operating voltages. The dynamotor voltages supplied are 12 volts for the heaters and 200 volts at 40 milliamperes for the plates.

The two transmitters used, *SK* and *SL*, are also similar, except for their frequency ranges which are 300 to 600 kilocycles for the long-wave transmitter and three to six megacycles for the short-wave transmitter. Both units incorporate a master oscillator and two amplifiers in parallel. Type *RL*-12*P* 35 tubes are used in all stages. The ratings of these tubes are included in their nomenclature. *R* means tube, *L* means power, 12 means filament voltage, *P* means pentode, and 35 denotes plate and screen dissipation (30 watts on the plate and 5 watts on the screen). The tuning of the two circuits is accomplished by iron-core variometers ganged together and controlled by a single knob. As in the receivers, four preset spot frequencies are also available, and test sockets are provided on the front panel to measure existing potentials. The dynamotor supplies plate voltage of 600 volts at 150 milliamperes. The emission is continuous wave only. However, in recently captured units radiotelephone has been added by grid-modulating the power-amplifier tubes. Output was measured as 65 watts, an efficiency of approximately 65 per cent. Frequency stability was found to be excellent. Fixed and trailing wire antennas are available to the radio operator and are tuned by remote-antenna-matching units by the use of Selsyn motors.

The *EZ*2 direction-finder receiver is used in conjunction with the *FuG* 10 and is adapted from the commercial German Telefunken direction finder of prewar days (1933) with few modifications. The frequency coverage is 165 to 1,000 kilocycles in two bands. The services provided are visual homing, aural homing, direction-finder bearings, and all-round communication. A conventional sense antenna is used in conjunction with an iron-core loop. The receiver is operated by the navigator who has mechanical remote controls located at his feet. The remainder of the equipment comprises local- and remote-control boxes, interphone amplifier, and dynamotors. These instruments have been designed to give complete control facilities where they are needed, and they accomplish this purpose.

The newest German airborne command set, the *FuG*

Essential substance of an address presented at a joint IRE–AIEE session of the AIEE winter technical meeting, January 27, 1944, in New York, N. Y.

Major General Roger B. Colton is chief of the engineering and technical service of the Signal Corps, United States Army, Washington, D. C.

Figure 1. Test panel for German air-borne radio-communication set FuG 10

16*Z*, is installed in all the newer bomber and fighter aircraft. The frequency coverage of the transmitter and receiver is 38–42 megacycles, with four spot frequencies set with click stops similar to the *FuG* 10 transmitters and receivers. In most installations, the *FuG* 16*Z* cannot be controlled locally in flight. We have found recent sets which provide for remote tuning of the receiver by the addition of a tuning motor and gang condenser. This enables the pilot to tune in to a station that may be off frequency a few kilocycles. Tests have proved this set capable of operation up to 250 miles at an altitude of 25,000 feet. Recent reports have noted an additional tuning mechanism and loop to facilitate navigational aid to the pilot.

The receiver *E* 16*Z* is a nine-tube superheterodyne. Only one type tube is used, the *RV*-12*P* 2,000. This tube is a radio-frequency pentode which is connected as a diode, triode, and pentode, as the occasion demands. The intermediate frequency is 3,000 kilocycles. Transmitter *S*16*Z* utilizes two *RL*-12*P* 35 transmitting tubes in a conventional modulated-output power-amplifier circuit. Output was measured as four watts, with a plate voltage of 400 volts or 210 milliamperes supplied back to the receiver and transmitter from the dynamotor unit. The oscillator circuit incorporates negative-temperature-coefficient condensers for frequency stability. The output is fed to the antenna-matching unit through a concentric cable. The modulator, located between the transmitter and receiver consists of two *RV*-12*P* 2,000 tubes in a two-stage circuit, one being the grid-modulator tube and the other the power-amplifier tube of the transmitter.

The German Notsender *NS* 2 sea rescue set is crystal-controlled and operates on 500 kilocycles, the international distress frequency. It sends an SOS. automatically. It can also be keyed manually. The power output is approximately 2.5 watts. The *NS* 2 antenna is hoisted by a balloon inflated by a hydrogen generator, which is activated by being placed in water. If a wind of seven miles per hour or more is blowing, a box kite is used in place of the balloon. The German *NS* 2 sea rescue set is the prototype of the American *SCR*-578.

In general German airborne electrical design is sound but not advanced. The mechanical design, incorporating die castings and specially designed parts, is of excellent quality. The primary design, with magnesium die castings fitted together with dowel pins and electrical plugs and jacks, is to facilitate easy servicing. An outstanding feature which becomes apparent upon examination of the airborne equipment is the neat cabling, which is "snaked" through in an orderly fashion and also is color-coded for ease in rewiring.

One thing the Germans have done to attain mass production is to standardize. In certain instances chassis are only partly filled with parts, a condition which indicates that an identical chassis is used for other installations. Tubes also have been standardized. Most of the German installations use the *RV*-12*P* 2,000 radio-frequency receiving tube or the *RL*-12*P* 35 power-amplifier tube. Of the 31 tubes used in the entire radio set *FuG* 10, these two types are the only ones used.

One of the first Japanese sets received by the Signal Corps was a receiver, transmitter, and dynamotor removed from a Zero fighter which crashed on a Pacific island in February 1942. The receiver—seven by nine inches—is a five-tube superheterodyne of obsolete construction compared to Signal Corps standards. The transmitter utilizes a crystal oscillator modulated by a single tube: Both tubes in the transmitter were marked *UX* 47, which is identical to the American *UY* 47, except that the plate lead is brought out of the top of the glass envelope.

The entire installation represents a command set of very crude construction. The coils are wound on Bakelite forms, with poor insulation and no tropicalization. Many of the parts were either bought on American distress markets about 1930–32 or are very good replicas of such parts. All the tubes bear American nomenclature and

Figure 2. German type EZ 2 direction - finder receiver used in conjunction with the FuG 10

are identical in construction to American glass tubes. The over-all electrical design and construction of this set is about ten years old from our viewpoint.

The latest Japanese airborne radio-communication set that has been received is the model 99 type 3, removed from a type-97 light bomber which crashed September 30, 1943, in China. The components consist of a transmitter and receiver, covering 2.5–5 megacycles; dynamotor, antenna-matching unit, control unit, and primary-voltage control box. The emission is continuous wave, modulated continuous wave, or phone. The normal range is about 75 miles at 10,000 feet, a possible range of 150 miles using phone under favorable conditions and altitudes, and a range up to 300 miles using continuous wave.

The receiver uses four type 6*F*7 tubes. These tubes are identical with the American 6*F*7, except that they use an octal base and metal envelope in place of the American seven-prong base and glass envelope. Each tube, being a pentode and triode in the same envelope, serves as a dual-purpose tube. The eight stages consist of one radio-frequency stage, one mixer, one high-frequency oscillator, two intermediate frequency stages, second detection beat oscillator, automatic-volume-control stage, and audio stage. Plate voltage was measured as 250 volts.

The transmitter utilizes a crystal oscillator, modulated by a single audio modulator tube. Both tubes are type 807s. The frequency-tuning control is a combination variometer–condenser and the antenna coupling is accomplished by the use of a variometer. When modulated continuous wave or phone is used, a 50,000-ohm resistor is placed in series with the oscillator plate to prevent the tube from exceeding its maximum rating during modulation peaks. Celluloid covers are placed on the variometers and movable condensers but are not dustproof. As in the receiver, all parts are clearly marked, and servicing is made easy by neat wiring and test panels.

It is recognized that the Japs are usually not original but are extremely quick to tool up and reproduce. The physical construction of model-99 type-3 set is exceedingly neat and facilitates easy servicing by clearly marked parts and test panels for measuring voltage. Wiring is neatly carried throughout and does much to dispel the idea that Japanese are capable only of copying. A number of points of design resembling American technique have been adapted rather than copied. However, it must be remembered that American and British designs have advanced to higher frequencies and the facility of push-button tuning for both transmitters and receivers.

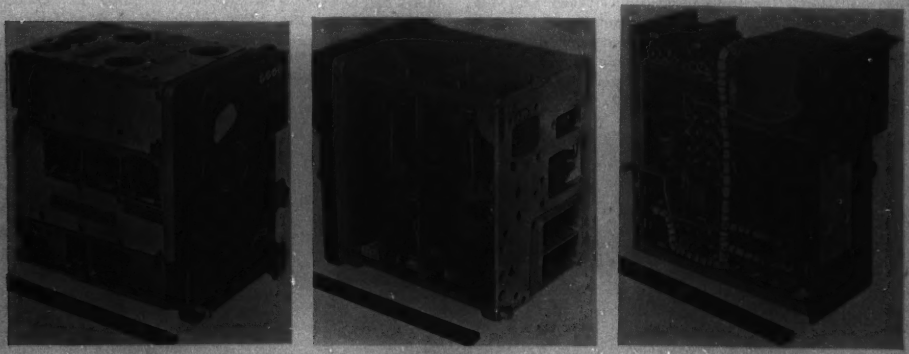
Generally speaking, Japanese ground signal radio equipment is similar to airborne sets. However, on the ground, wire communication and visual communications are both utilized in signaling in addition to radio.

Among the German ground signal equipment there is the German tank radio set consisting of the transmitter 10*WSe* and receiver *UKWEe*. This is an amplitude-modulated set covering a frequency range of 27.2–33.4 megacycles. The transmitter and receiver operate from separate external dynamotor power supplies. Normally the drain from a 12-volt storage battery is 7.2 amperes for the transmitter and 4.0 amperes for the receiver. Under these conditions the transmitter output into an antenna load of 40 ohms is five watts.

The transmitter and receiver utilize identical tuning mechanisms. A large circular dial face clearly marked in 50 divisions is used. Provision is made for setting up two preselected "flick" channels. An uncalibrated auxiliary dial is employed on the receiver to provide fine tuning. The dial of the transmitter is calibrated very accurately, and it is possible that netting may be accomplished without the use of auxiliary equipment. It is a very simple matter to set up the preset channels. Transmitter dial error does not exceed 7.5 kilocycles throughout the dial scale, and dial "flick" resettability error has been found to be less than 750 cycles per second.

The receiver is a conventional superheterodyne. The intermediate frequency is three megacycles and operates at less than signal frequency. The oscillator is self-excited and is stabilized by the use of temperature-compensating condensers. The transmitter is a self-excited oscillator with a single-tube final amplifier using an *RL*-12*P* 35 tube in each stage. The oscillator operates at one-half the output frequency. One type-*RV*-12*P* 4,000 tube is used as a grid modulator and modulated-continuous-wave oscillator.

As in the receiver, the transmitter oscillator is stabilized by the use of temperature-compensating condensers.



A. Receiver E16Z *B. Transmitter S16Z* *C. Modulator BG16Z*

Figure 3. Newest German air-borne radio command set FuG 16Z

Figure 4. German Notsender sea rescue radio set NS 2

Neon-tube voltage stabilizers are used in the oscillator-plate supplies of both the receiver and transmitter. During tests on battery-voltage drift the transmitter varied no more than plus or minus 250 cycles for battery voltages ranging from 10 to 14 volts. The receiver varied less than plus or minus four kilocycles for the same range of battery voltages, representing 0.013 per cent at 30 megacycles. As to temperature drift, the transmitter and receiver displayed a high degree of stability.

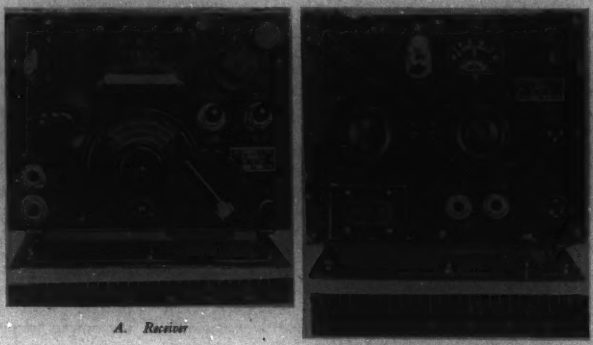
The transmitter stability between +30 degrees centigrade and +75 degrees centigrade is comparable to that which might be expected of a crystal-controlled transmitter. The effects of vibration were found to be negligible. This equipment when used in battle had apparently been sealed against fine sand by means of pitch inserted in the cracks between the front panels and the housing.

The German Tornister or pack set *Fuf* is the one used in greatest quantities by the communications personnel of the ground forces. The set, a transmitter–receiver combination, capable of operation on continuous wave or voice, is housed in two cases, one containing the transmitter and receiver and the other containing the power supply and remote-control unit and accessories. This equipment operates on a frequency range, as far as the transmitter goes, of from 4,500 to 6,670 kilocycles, while the receiver is capable of receiving a wider range of from 3,000 to 6,600 kilocycles.

The transmitter is a modulated-output power-amplifier type. The receiver is the conventional superheterodyne pack. The intermediate frequency of the receiver is 2,000 kilocycles, and the set can be calibrated quickly by the use of a glow-quartz resonator. The use of remote operation by the Germans is typical of all of their ground signal sets. It is possible, for example, by using this remote-control unit, for the officer in the remote operation to modulate the transmitter at the observer's point merely by flicking the switch. In a similar manner it is also possible by use of a bell located at the remote location, for the officer to talk back, modulating the pack set at the observer's point. Then there is a third fitting on the switch which allows the remote line to be operated as a field telephone.

The German telephone carrier unit model *TF-b2* is comparable to the Bell System's type-*H*-1 carrier equipment. It provides one telephone circuit in addition to the regular voice frequency when operated on a two-wire line. Signaling is accomplished by shifting the carrier frequency 500 cycles. Transmission is single side-band suppressed carrier; in one direction it transmits the upper side band of 11 kilocycles, and in the other direction it transmits the lower side band of 11 kilocycles. It may be used at either end of a circuit by means of a switch selecting either terminal, *A* or *B*. The telephone channel transmitted is from 250 cycles to 2,200 cycles. The equipment operates entirely from a 12-volt battery; total drain is about two amperes. A built-in-vibrator power pack is used for plate voltages and supplies 180 volts; total plate-current drain of the set is about ten milliamperes.

The modulator used is a ring modulator, metallic-rectifier type having similar characteristics to the varistor used in this country. A 20-cycle incoming signal will operate



A. Receiver *B. Transmitter*

Figure 5. Japanese air-borne radio-communication set, model 99, type 3

Figure 6. German tank radio set consisting of transmitter 10WSc and receiver UKWEe

Figure 7. German Tornister or pack transceiver, type Fuf, showing battery box (left), handset, and remote-control ringing generator

relays to produce the 500-cycle shift of the carrier and also cause the carrier to be transmitted. A guard band is used; one relay and associated circuit rejects 500 cycles, another relay and circuit rejects all voice frequencies except 500 cycles. A relay chain produces 20 cycles to send a received ring out to the other station. The range is about 16 miles when used with German field-telephone cable; this is a cable similar to American spiral four. On open-wire lines the range is approximately 125 miles. The *TF-b*1 is a similar unit that operates with a carrier frequency of 5,500 cycles. The *TF-b*2 and *TF-b*1 can be used on the same line, giving a total of three telephone circuits. Two *TF-b*2 units can be used back to back, at intermediate points, as a repeater.

The German telephone dial unit follows, generally, the conventional design of American dials produced by "independent" telephone manufacturers, and its performance seems satisfactory. The assembly of the operating mechanism, however, is not so compact, nor its operation so quiet as American-made dials. The ringer is an electromagnetic nonpolarized reed-type buzzer and weighs 1.8 ounces.

Two German field telephones, model 33 were examined in the Signal Corps laboratories and found identical with United States Army *EE*-8, except for the finish of the cases and type of instrument wire. The handset is similar to the Signal Corps type *TS*-9 (used with the *EE*-8) but employs a lever-type transmitter switch. Talking tests indicate that both the German field telephones compare favorably with ours.

From all indications, the majority of the German field-wire installations use ground-return circuits. The latest German field wire is a single conductor of eight steel strands and one of copper. Evidence has been found of one strand of aluminum instead of the copper. It is covered with a bright red synthetic insulation. The tensile strength of the wire is excellent, but the handling of it is difficult.

The Japanese direction-finder and intercept receiver model 94 is a loop direction finder covering the frequency range of 100 to 2,000 kilocycles. The receiver is a tuned radio-frequency set employing three stages of radio-frequency amplification, a heterodyne detector, and two stages of audio amplification. The components and circuits employed are comparable to those used in American sets of the 1925–30 period. The loop assembly consists of a T-shaped mast and crossarm, forming a frame, upon which is wound a six-turn unshielded diamond-shaped loop approximately 16 square feet in area. The outstanding feature of the Japanese direction finder is its portability. This makes it ideal for use in jungles or other difficult terrain.

The Japanese "walkie talkie" model 66, picked up in a creek at Kiska, is a superregenerative transceiver similar to those used in the United States by the radio amateurs during the early 1930's. This set uses a type *UZ*-12*C* dual-triode tube similar to the American type 30. Various bands of frequencies are used in the 2-megacycle to 90-megacycle range. The power requirements are 6 volts and 150 volts direct current, supplied by batteries in a separate box. In general, the layout of both parts and wiring is complex and difficult to trace or repair. The front panel is complicated by switches and dials, all of which have to be adjusted for any one frequency. In comparison with the United States "walkie talkies" and "handie talkies" using superheterodyne receivers and crystal control, the Japanese set is very difficult to operate satisfactorily under conditions of humidity and woody terrain.

The Japanese command transmitter, model 94, number 2, type *B*, is a man-pack set designed for use at Division Headquarters. This radio set is an exception to the usual Japanese run of inferior-quality equipment. It is very well constructed, and its ruggedness, simplicity, and general excellence of design are worthy of note. Considering the specific purpose for which this set was designed, it is unexcelled by any similar American equipment.

It consists of a transmitter, receiver, and gasoline-engine power-supply unit. Frequency coverage of the transmitter is from 950 to 6,675 kilocycles, and the trans-

Figure 8. German field telephone, model 1933, complete with Telefunken handset and ringing generator (left) which is identical and interchangeable with United States Signal Corps type EE-8-A set (center), and Japanese field telephone (right)

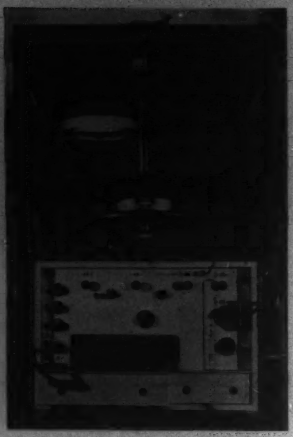


Figure 9. Japanese special direction-finder and intercept receiver model 94, type 7, mounted in frame support and including azimuth and shaft connecting with loop antenna on top

Figure 10. Japanese "walkietalkie"

Frequency range 2,500 to 4,500 kilocycles. Power-supply battery 1.5 to 135 volts. Comparable to SCR-194 except not ultra-high frequency

mitter power output averages about 85 watts over this range. The receiver covers from 140 to 15,000 kilocycles. It is superheterodyne type with a 100-kilocycle intermediate frequency for the range 140 to 1,050 kilocycles. For the remainder of the frequency range up to 15,000 kilocycles the intermediate frequency is 400 kilocycles. The receiver is powered by batteries, while the transmitter uses a very well-designed gasoline-engine unit. This machine delivers approximately 914 watts and weighs 103 pounds complete, which is approximately one third of the weight of our corresponding power unit, the *PE*-49. The supply to the transmitter itself is five amperes at 12 volts and 175 milliamperes at 1,300 volts.

The Japanese use ground-return circuits in their field-wire systems; the Japanese single-wire-conductor field wire employs conductor strands the same in number and material as those of standard Signal Corps field wire *W*-110-*B*, but with a smaller diameter. The wire had high tensile strength and low abrasion resistance. The electrical characteristics are not so good as might be anticipated from the construction. There is very little evidence of the Japanese using field switchboards, but they utilize a "party-line" system employing ground return instead.

The Japanese field telephone is contained in a metal-reinforced wooden case. The circuit is of the conventional design with the exception of a buzzer and key arrangement that is used to send code. A spare transmitter unit is provided with each telephone for replacement purposes. The case cannot be waterproofed, because of the hinged front wall, the buzzer-key opening, and the louvers. A portable lightning arrester is provided consisting of a black rubber case, two line-binding posts, fiber-encased fuses, choke coils, metal-discharge blocks, mica insulators, and flexible ground lead. Compared with United States standards, the general mechanical construction of this set is inferior. Talking tests indicate that the Japanese field telephone does not compare favorably with the Signal Corps telephone *EE*-8.

In general, German ground components are well built and thoroughly designed. All parts are marked with terminal numbers to facilitate easy replacement. Wiring is small and neatly cabled. Dials are well machined and very accurate. Backlash is at a minimum. In all sets emphasis is placed on design for mass production.

Japanese ground parts are of rather obsolete design and in some cases very inferior to American parts. Japanese coil forms are, in general, very poor. Usually wooden or molded-mud insulation coils are used, even in equipment operating up to 90 megacycles. Jap transformers are usually unpotted, and there is no evidence of weather-proofing. Jap crystals and holders are, however, of good design. Several Jap holders examined have been very accurately molded; crystals are accurately ground.

Generally speaking, it may be said that German equipment is the best enemy equipment and Japanese equipment is probably the poorest. However, both German and Japanese equipments have points of interest to engineers, and we *can* and *do* learn from all our enemies. It is the right of American engineers to know as much as is consistent with military security about the enemy's communications equipment. This is the first complete discussion of enemy signal apparatus that has yet been made public by the Signal Corps.

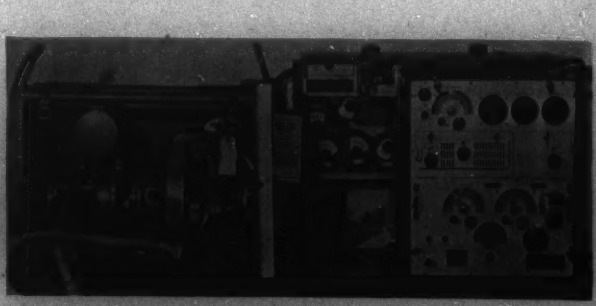


Figure 11. Japanese mobile command net transmitter, 200 watts, model 94, number 2, type B, for frequency range 950 to 6,675 kilocycles, complete with power-supply gas-engine-driven generating set (left), 1,300 volts (similar to PE-49D)

INSTITUTE ACTIVITIES

Preliminary Arrangements for Summer Technical Meeting

Arrangements now are being made for the summer technical meeting of the AIEE to be held in St. Louis, Mo., June 26–30, 1944. Meeting headquarters will be in the Hotel Jefferson, which has ample meeting room facilities including some air conditioned rooms. The annual meeting of the Institute will be held on Monday, June 26.

Three important anniversaries will be commemorated during the meeting. The 100th anniversary of the Morse telegraph will be recognized in a special session with papers on telegraphy. The 60th anniversary of the founding of the AIEE will be celebrated, as well as the 40th anniversary of the International Electrical Congress. The first international electrical congress was held at St. Louis in 1904.

Tentative arrangements are being made to schedule 27 technical sessions and conferences. The subject matter will range throughout the entire breadth of professional interest in the electrical industry.

Those making the arrangements for the meeting are B. D. Hull, *chairman;* I. T. Monseth, *vice-chairman;* L. L. Crump, *secretary-treasurer;* F. A. Cooper, Jr., chairman, St. Louis Section. Subcommittee chairmen: C. B. Fall, *finance;* C. H. Kraft, *meetings and papers;* B. T. McCormick, *registration and information;* R. G. Meyerand, *hotels;* E. S. Rehagen, *hospitality;* Guy W. Thaxton, *transportation and trips;* L. F. Woolston, *publicity.*

SECTION • • • • •

Lee Explains Plane-Speed Recorder to Akron Section

An electronic device, which automatically reads recording instruments and prints the readings on a chart was described by E. S. Lee (F '30) engineer in charge of the general engineering laboratory of the General Electric Company, Schenectady, N. Y., at a recent meeting of the Akron Section of AIEE. The instrument is used to measure the speed of motors used in airplane wind-tunnel tests.

The behavior of newly designed airplanes is ascertained by testing models powered with small-scale electric motors in a wind tunnel. Data about the performance of the miniature motors must be determined with great precision in order that the results may be transferred accurately to the full-sized planes, Mr. Lee said. The indications picked up by electron tubes from the motors under test cause the rotation of a tiny thyratron-controlled motor which in turn drives wheels carrying type. When the operator takes a reading, he presses a button and the type wheels print their setting at that moment. Mr. Lee added that the mechanism may be adjusted so that it gives the equivalent of readings on a scale more than eight feet long.

STANDARDS • • •

The following AIEE Standards may be obtained from AIEE headquarters, 33 West 39th Street, New York 18, N. Y., at the prices specified. A 50 per cent discount is allowed to AIEE members on single copies.

Modification and Supplement to AIEE Standard 45. This supplement to AIEE Standard 45, "Recommended Practice for Electrical Installations on Shipboard," is a revision issued January 1, 1944, of the first edition issued April 1, 1943. These modifications of Standard 45 are issued solely for the purpose of conserving critical materials and are to be used in conjunction with the present Standard 45. Copies are 50 cents each.

Standards for Capacitance Potential Devices and Outdoor Coupling Capacitors. This AIEE Standard 31, as approved January 27, 1944, is a revision of the proposed Standard of the same title issued in report form for trial use in December 1941. Copies are 30 cents each.

American Standard Z32.10. Graphical Symbols for Electronic Devices. This American Standard, approved this year, is a revision in part of the former American Standards *Z*10*g*3–1933 and *Z*10*g*6–1929 (AIEE numbers 17*g*3 and 17*g*6). This Standard is intended to cover the symbols for electronic devices known as electron tubes, and was developed to co-ordinate the various basic symbols for those devices. Copies are 20 cents each.

American Standard C19. Industrial Control Apparatus. This is a revision of the 1928 edition of the American Standard *C*19 (former AIEE Standard 15). It covers definitions; classification of controllers, switches, and resistors; kinds of protection, enclosure for protection of persons and apparatus; duty and service; ratings; temperature limitations and limitations other than heating; temperatures, and dielectric tests. Copies are 50 cents each.

Bushing Standard Approved as American Standard

The American Standards Association has approved, as an American Standard, the Standards for Apparatus Bushings and Test Code for Apparatus Bushings (number 21), which was developed by the AIEE.

The standards for apparatus bushings specifically cover outdoor bushings for large apparatus; cover-type bushings for small apparatus; and indoor bushings for all types of apparatus except dry-type instrument transformers, air-blast transformers, dry-type regulators, circuit breakers rated below 5,000 volts, and nonoiltight oil circuit breakers rated 50,000 kva or less. The main specification includes requirements for service conditions, definitions, ratings, heating, dielectric tests, and nameplate markings, and has a table of standard test voltages for apparatus bushings. The standards are not intended to apply to wall bushings, cable potheads, nor insulators for back-connected disconnecting switches, although many of the principles may be applicable.

The Test Code for Apparatus Bushings, which is published with the standards as an appendix, pertains to tests on apparatus bushings apart from those tests on the assembled apparatus. There is a classification of bushings tests, test procedure, adjustment of conditions for wet test, standard test conditions, correction factors, and routine and design tests.

The Standard is now available and may be obtained for 40 cents a copy from the ASA, 29 West 39th St., New York 18, N. Y. Members of the AIEE are allowed a 50 per cent discount.

ABSTRACTS • • •

TECHNICAL PAPERS previewed in this section will be presented at the AIEE North Eastern District meeting, Boston, Mass., April 19–20, 1944, and are expected to be ready for distribution within the current month. Copies may be obtained by mail from the AIEE order department, 33 West 39th Street, New York 18, N. Y., at prices indicated with the abstract; or at five cents less per copy if purchased at AIEE headquarters or at the meeting registration desk.

Mail orders will be filled AS PAMPHLETS BECOME AVAILABLE

Air Transportation

44-72—A Unit for Balancing the Voltages of Three-Phase Aircraft Inverters Supplying Large Single-Phase Loads; *Sydney Wimpis (A '42). 15 cents.* Increased electrification of military aircraft has necessitated putting large single-phase loads on three-phase inverters without unbalancing the inverter's terminal voltages. A balancer unit that makes a single-phase load appear as a balanced three-phase load to the power supply is described. Extensive test data are furnished and various advantages and limitations of the unit are discussed. The basic vector diagram plus certain design considerations are also treated.

44-81—A-C and D-C Short-Circuit Tests on Aircraft Cable; *J. C. Cunningham (A '42), W. M. Davidson (A '42). 25 cents.* Short circuits between aircraft cables and between

cable and metal structure were investigated in the laboratory to determine (1) reasons for the apparent freedom from sustained faults in present 28.5-volt d-c systems despite heavy gunfire damage, and (2) whether faults will burn clear as readily on proposed 120-volt d-c and 208/120-volt 400-cycle systems. The tests show (1) that freedom from sustained faults on 28.5-volt systems can be attributed mainly to spreading of wire strands by gunfire and the high level of short-circuit current at most locations, and (2) that ability to burn clear would not be materially different at the higher voltages if as much short-circuit current were available. The use of protective devices to isolate faulted cables will reduce fire hazard if short-circuit current is less than 2,000 amperes for number 8 cable, 1,000 amperes for number 14 cable, and 300 amperes for number 20 cable. For 400-cycle systems, protective devices usually will be required to clear faults with minimum generation in time to prevent loss of synchronism or stalling of motors.

44-82—Damping Cylinders for Aircraft Gyroscopes; *F. R. Sias, J. H. Wright (M '43). 20 cents.* Air-damping cylinders have been applied successfully to the erecting system of a gyroscope horizon instrument for aircraft. In so doing, a degree of damping is obtained which would not be possible by other means within the same limitations of space and weight. It is shown that these cylinders do not act as pure damping agents, but introduce an elastic component of force which varies in relative magnitude with the amount of compression of the confined air and its absolute pressure. By a method employing an electrical analogy, the factors which control the ultimate damping effect are analyzed, and it is shown that cylinder design must follow certain dimensional requirements dictated by the dynamics of the whole oscillating system. These considerations determine the minimum size of cylinder which can be used in a given application and also the piston clearance which gives maximum damping effect.

44-83—Aid to Quality Control in the Manufacture of Aircraft Generators; *F. M. Potter. 15 cents.* Aircraft generators are designed for high output, low weight, small size, and wide speed range. These limitations require designs which do not permit normal allowances for material and manufacturing variations. Small variations in the material and manufacturing processes result in wider variations in output characteristics than in conventional machines. It is the purpose of this paper to discuss certain of these variations and their effect on the output characteristics of the machine and to illustrate means of checking and controlling these factors.

44-84—Blast-Tube Cooling for Aircraft Generators; *C. G. Veinott (M '34). 20 cents.* Established principles of hydraulics are used to develop and explain fundamentals of blast-tube cooling. It is shown that the pressure–volume curves of a blast tube can be determined by flight tests, and that the pressure-volume of a generator can be determined in the laboratory. From the two pressure–volume curves, the air flow through the generator in flight can be predicted without an actual flight test on the generator. This procedure would save many flight tests, if pressure–volume curves of various blast tubes were available. It is shown that the pressure–volume curve of a blast tube can be determined by open-end and closed-end readings on the blast tube and the complete curve expressed in terms of two constants readily determined from these readings. Once values of the constants are established, air-flow calculations become as simple as the application of Ohm's law. The theory also covers generators with an internal fan. A plea is made for accurate blast-tube data and for better specifications on blast cooling. A suggested form of blast-tube specification is given.

Electrical Machinery

44-75—A Graphical Analysis of the Voltage and Current Wave Forms of Controlled-Rectifier Circuits; *P. T. Chin (A '41), E. E. Moyer. 30 cents.* Controlled rectifiers employing gaseous discharge tubes are used more and more frequently in the industrial field because of the ease of controlling the output voltage and the high conversion efficiency. The voltage and current wave forms at the different parts of controlled-rectifier circuits are often nonsinusoidal and discontinuous due to the one-way valve action of the rectifying elements. This paper presents a graphical method of constructing the voltage and current wave forms based on a few well-known fundamental principles of electrical engineering. The method is presented step by step and a few typical examples are shown to illustrate its validity.

44-86—Behavior Factors of Rectifier-Driven D-C Motors; *Victor Siegfried (M '38). 15 cents.* This paper proposes to analyze the behavior of d-c motors when subjected to pulsating direct current from rectifier sources. It is felt that this phase of the application of electronic drives has been given insufficient consideration, particularly in regard to (1) heating value of the current waves, (2) voltage stresses upon the insulation and commutator resulting from the high peak values involved, and (3) torque pulsations and noise resulting from this type of wave form. Experimental and theoretical approaches are made to illustrate the possible ratios of effective heating value to the average value of typical wave shapes encountered in electronically driven motors. The degree to which these values approach each other varies with the load on the machine and also with the number of tubes used in the rectification. The conclusion is reached that this problem is most accute in machines of small rating where the mechanical inertia is low, and tube capacities permit use of but one or two tubes for economy of materials. This very condition aggravates both the heating and the vibration problems, and may require overmotoring, the application to allow for thermal capacity. Vibrations will also show up in work on such machines as grinders and in chatter marks on the finished surfaces. With many tubes (phases) in the rectifier the current output approaches conventional continuous-current practice, and standard-design motors may be used. The over-all conclusion to be drawn is that factors not at first apparent must be considered in the application of rectifier drives to any given motor or load and no over-all design factor may be presumed to apply to all cases.

44-87—Design of Variac Transformers; *Edward Karplus (M '44). 15 cents.* The paper describes a new continuously adjustable variable-ratio autotransformer for regulation of line voltage from zero to above line voltage. Operation of the new transformer depends on the application of a carbon-composition contact directly on the turns of the transformer winding. In sliding over the winding, the contact taps off any desired number of turns. The resistance of the contact prevents excessive heating when adjacent turns are short-circuited. The winding has to be applied in a single layer and the core of the transformer is made toroidal in shape to allow compact design. The problem of contact design for minimum losses and the characteristic of a single-layer transformer winding are discussed in detail.

Electronics

44-78—Development of Excitron-Type Rectifier; *H. Winograd (M '39). 30 cents.* This paper describes the design and development of the excitron-type rectifier which is the latest addition to the family of mercury-pool-type power rectifiers. The excitron is a single-anode rectifier with a continuous excitation arc maintained at the cathode when in operation. The experimental test method used in the development of the excitron is described. This method is based on the measurement of the inverse (ion) current to the anode which current results from the residual ionization at the conclusion of the forward firing period. The relationship between the inverse current and arc-backs is discussed and test results are given on a number of experimental excitron designs.

44-79-ACO—The Application of Broad-Band Carrier Systems to Telephone Cables; *J. P. Thurber. 20 cents.* In planning for additional long-distance facilities between Boston, Mass., and Portland, Me., the important considerations which led to the choice of the route finally followed and the different types of facilities which might be placed on this route are outlined. The reasons for the selection of broad-band-cable carrier systems working in two 19-gauge cables are given and the laying of these cables by plowing them into the ground directly from the reel is described briefly. The main points which had to be considered before arriving at the final location of the repeater stations are reviewed and the precautions which were necessary to keep the cross-talk in the cable plant at a minimum are covered. A brief description of the equipment and operation of the systems is given besides.

Power Generation

44-71—Vibration Protection for Rotating Machinery; *R. L. Webb (M '35), C. S. Murray (A '34). 15 cents.* Vibration protection becomes desirable for rotating machinery when it is operated with certain defects. Electric generators may be operated with a

single ground on the rotating-field circuit without harm but the potential hazards of a second ground at another point on the same circuit are so great that the need for protective equipment for automatic disconnection of the generator is evident. Double grounds on a rotating-field circuit may short-circuit a large part of the winding, unbalance the magnetic field, and set up vibrations of such serious magnitudes that the machine may be wrecked. A method for obtaining satisfactory vibration protection for rotating machines has been developed. It uses equipment most of which is already on hand or readily available to most companies operating important machinery. The only additional construction required is an electronic amplifier. The equipment, its operating characteristics, wiring, and performance are described in this paper. The protective equipment described has been in service on one machine since the latter part of 1942, furnishing entirely satisfactory service. Another machine was protected in a similar manner for about three months until it was found convenient to rewind the field.

44-85—Prevention of Rotor-Winding Deformation on Turbogenerators; *J. G. Noest* (*M* '36). *25 cents.* This paper discusses the phenomenon of rotor-winding deformation, which has been the cause of a number of failures in large turbogenerators. Rotor-winding deformation is shown to be the result of the combined action of centrifugal force and temperature change. Most of the deformation is caused in starting the generator, when the rotor winding is heated from ambient to operating temperature, and restrained from axial expansion by the centrifugal force. Preheating of the rotor winding by means of current in the winding at low generator speed is shown to be effective in reducing deformation as it permits the rotor conductors to expand to a length corresponding to a time-weighted average operating temperature, without the restraint caused by centrifugal force. The rotor winding thus reaches rated generator speed practically free from mechanical stress, and subsequent temperature changes produce only small values of stress in the conductor material.

Power Transmission and Distribution

44-73-ACO—Reliability of Compressed-Gas Insulation; *J. D. Cobine* (*M* '41), *E. C. Easton* (*M* '44). *15 cents.* Measurements were made to determine the length of time during which compressed nitrogen can withstand a nearly rectangular voltage surge. The voltage was applied between spheres in gas under pressure variable from one half to six atmospheres. For each set of measurements the maximum value of the applied voltage was set at a constant percentage above the static breakdown voltage. For a fixed percentage of overvoltage the most probable time lag (before the breakdown of the gas) dropped rather sharply from large values of several thousand microseconds to values of five to ten microseconds as the pressure was increased beyond a certain critical value. Thus, whereas the static breakdown voltage increases with an increase of gas pressure, the probability that the gas will break down under the stress of short voltage surges is much greater at high pressure than at lower pressures.

44-74-ACO—110-Kv Tie Line Uses Progressive Design; *E. A. Church* (*A* '29), *E. G. Stebbins. 15 cents.* An "H" frame wood-pole line completed by the Boston Edison Company in December 1941 was designed to have the highest impulse strength consistent with reasonable cost. In this line the wood crossarms and the pole tops are used as insulation in series with the insulators. For d-c and a-c voltages of low frequency, the wood has very little value as an insulator. However, for impulse voltages of very short duration, wood has an impulse strength of about 87 kv per foot, and can be used to advantage in series with the insulator string to raise the impulse strength of the line. The line is equipped with two steel overhead ground wires, mounted on the pole tops, seven feet above the crossarms, and sagged to give from 13 to 20 feet of clearance at midspan depending on the length of span which varies from 300 to 500 feet. These ground wires are connected to a continuous steel counterpoise by means of leads connected to the ground wires eight feet from the poles and fastened to the poles seven feet below the crossarms to obtain 13 feet of wood between the insulator string and ground. No outages have been recorded for this line during two lightning seasons.

44-76-ACO—Conversion of Montaup Electric System From 66 Kv to 110 Kv; *W. B. Carnie* (*A* '39). *15 cents.* This paper describes the conversion of a transmission system from 66 kv delta to 110 kv wye in one week end without interrupting service to the customers. To provide for increased loads additional transformer and 110-kv tie line capacity as well as retention of low-voltage ties were included in the change. Preparation included an a-c calculating-board study of voltage and load conditions.

44-77-ACO—Improving the Performance of 110-Kv Lines; *D. H. Hathaway, A. B. Jones. 15 cents.* This paper reviews changes made in an existing two-circuit steel-tower transmission tie line (part of the Edgar–Walpole–Millbury tie) with a record of unsatisfactory operating performance, to increase its reliability to the point at which it now constitutes a dependable intersystem tie. The relaying system was improved in several respects. Expulsion protector tubes were installed at each conductor on each tower to improve performance with respect to lightning. High-speed trip coils and arc-quenching contacts were installed in the circuit breakers to decrease circuit interruption. These changes have effected the desired improvement. Because of the increasing importance of the line for power interchange between two large systems, the transformer capacity at the Edgar station has been increased nearly 100 per cent and carrier-current relaying and automatic reclosing of the line's oil circuit breakers are about to be installed to reduce the duration of circuit outages.

44-80—Measured Electrical Constants of 270-Mile 154-Kv Transmission Line; *C. A. Strifus* (*M* '44), *C. S. Roadhouse, R. B. Gow* (*A* '35). *25 cents.* Electrical constants were measured by applying 2,400/4,160-volt potential to appropriately connected conductors at one terminal. Indicating instruments furnished data for obtaining open- and short-circuit impedances of positive-phase, zero-phase, and one-conductor-and-ground networks. These impedances were converted to fundamental *ABCD* constants, and then to unit resistance, inductive reactance, and capacitive susceptance, and to characteristic or surge impedance. Theoretical constants computed from line dimensions are compared with measured values. Results indicate good agreement between measured and computed positive-phase constants. Measured and computed capacitive susceptances agree closely for the zero-phase and one-conductor-and-ground networks. Greatest difference occurs between measured and computed unit resistances and inductive reactances in these two networks, due possibly to the difficulty of including in computations all effects varying with current density, of resistance and reactance of shield wires; indefinite value of resistivity in earth return path; and variations in conductor and shield wire configuration.

Future AIEE Meetings

North Eastern District Meeting
Boston, Mass., April 19–20, 1944

Summer Technical Meeting
St. Louis, Mo., June 26–30, 1944

Pacific Coast Technical Meeting
Los Angeles, Calif., Aug. 29–Sept. 1, 1944

PERSONAL ....

I. B. Stiefel (A '18) formerly manager of industrial relations, Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa., has been appointed assistant to the vice-president in charge of industrial relations. Mr. Stiefel has been with the Westinghouse company since 1912 when he entered its graduate student course. He has been assistant superintendent of coils and insulation, assistant superintendent of the motor division, superintendent of mill and foundry, and manager of the feeder division number one. Since 1937 he has been manager of industrial relations. **F. R. Benedict** (A '40) formerly manager of the New England district engineering and service department of the Westinghouse company has been appointed manager of product performance analysis. Associated with the Westinghouse company since 1928, Mr. Benedict was manager of the company's Trafford laboratories and impulse laboratory from 1936 to 1938. He was appointed liason engineer on the chief engineer's staff in 1938, consulting and application engineer in the district engineering and service department in 1940, and manager of that department for the New England area in 1941. **H. H. Chapman** (A '36, M '42) formerly manager of the Minneapolis (Minn.) office of the Westinghouse company, has been made manager of the company's

transportation department. Mr. Chapman joined the company in 1920 and has been manager of the Minneapolis office since 1936.

H. L. Rawlins (A '30, M '41) formerly section engineer in the Westinghouse company has been named manager of the protective devices engineering department. Mr. Rawlins, who holds the degree of master of science from Ohio State University, has been associated with the company since 1928 and has been section engineer since 1936.

A. W. Hill (A '38, M '41) formerly of the switchgear engineering department of the Westinghouse company has been appointed manager of power circuit breaker engineering. Mr. Hill has been with the company since 1920 and in the switchgear division since 1925.

A. M. Dudley (A '03, F '13) engineering representative, patent department, Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa., retired recently. Born in Cincinnati, Ohio, in 1877, Mr. Dudley received from the University of Michigan the degrees of bachelor of science in 1902 and electrical engineer in 1931, and from the University of Pittsburgh the master of science degree in 1933. He was honored by the University of Michigan with the degree of doctor of engineering in 1939. Mr. Dudley joined the Westinghouse company in 1904 as a control engineer and later became engineering supervisor of development, manager of development engineering, marine application engineer, and finally engineering adviser in the patent department. For many years he was engaged in recruiting young engineering graduates for the Westinghouse graduate student course. He is the author of "Connecting Induction Motors," "Induction Motor Practice," a correspondence school course in electricity, a Westinghouse extension school course, and the article on electric motors in the current edition of the Encyclopedia Britannica.

L. A. Howland (A '00, F '13) vice-president and general manager, Queens Borough Gas and Electric Company, Far Rockaway, N. Y., has retired. Mr. Howland entered the employ of the Stanley Electric and Manufacturing Company, Pittsfield, Mass., in 1895 doing testing and construction work. Subsequently he had charge of construction and testing for the Royal Electric Company and for the Canadian General Electric Company, Montreal, Que. With the Newfoundland Light and Power Company, St. Johns, from 1902 to 1906 he was engaged in electric light and power and street railway management, and in 1906 was appointed manager of the Nassau Light and Power Company. Joining the Queens Borough company in 1909 as general superintendent he was elected vice-president in 1926. In 1927 he was appointed vice-president and general manager and in 1933 was made a director.

F. C. Stockwell (A '12, M '27) professor of electrical engineering and dean of the graduate school, Stevens Institute of Technology, Hoboken, N. J., has resigned as dean of the graduate school. Professor Stockwell has been a member of the faculty since 1907 and has been dean of the graduate school since 1939. **W. L. Sullivan** (A '34, M '42) formerly assistant professor of electrical engineering, has been appointed associate professor and director of the graduate school. Professor Sullivan, who is a graduate of Massachusetts Institute of Technology, joined the faculty as instructor in 1934. He was appointed assistant professor in 1936 and assistant to the dean of the graduate school in 1939. **L. A. Hazeltine** (F '35) professor of physical mathematics, has resigned to devote his attention to research work. He served on the faculty from 1907 to 1925 and recently since 1933.

E. E. Minor, Jr. (A '35, M '41) consulting engineer and research and development engineer, Glenn L. Martin Company, Baltimore, Md., has been appointed vice-president and head of the manufacturing and development division of All American Aviation, Inc., Wilmington, Del. Born in 1907, he holds the degrees of bachelor of engineering (1930) and doctor of engineering (1934). He conducted an investigation of space charge in liquid dielectrics from 1931 to 1934. In 1935 and 1936 he worked on job analysis for the United States Department of Labor, Washington, D. C., and in 1936 joined the Glenn Martin company as staff electrical engineer, later becoming research and development engineer. Doctor Minor was first chairman of the AIEE committee on air transportation in 1940.

L. B. Fuller (A '03) formerly chief engineer, Utah Power and Light Company, Salt Lake City, has become engineering consultant for the company. Before joining the Utah Power and Light Company in 1913, Mr. Fuller superintended electrical construction in Utah and Idaho for the Telluride Power Company and the Beaver River Power Company. He was employed by the Utah Power Company first as construction superintendent on various hydroelectric stations and from 1919 to 1927 was employed on construction executed by the Phoenix Utility Company for the Utah Power company. In 1927 he was appointed assistant superintendent of power by the Utah Power company, and in 1929 superintendent of power. Since 1937 he has been chief engineer of the company.

Maurice Holland (A '23, M '30) industrial research adviser, New York, N. Y., has been appointed industrial research adviser to the Armour Research Foundation, Chicago, Ill. Mr. Holland was director of the division of engineering and industrial research of the National Research Council from 1923 to 1943. He served as director of the mission on industrial exploration to South America in 1941 conducted under the auspices of the Co-ordinator of Inter-American Affairs and the National Research Council. He was a delegate to the First World Power Conference in London, England, in 1924 and to a number of other international meetings.

R. C. Griffith (A '35) director of research, Heald Machine Company, Worcester, Mass., is not the R. C. Griffith recently appointed manager of engineering and research by the Denison Engineering Company, Columbus, Ohio, as was reported in the December 1943 issue of *Electrical Engineering*. The latter is not an AIEE member.

OBITUARY • • • •

Thomas Mayo Roberts (A '02, M '12) retired associate electrical engineer, procurement division, public works, mechanical engineering section, Treasury Department, Washington, D. C., died January 10, 1944. Mr. Roberts, who was born January 22, 1867, in The Dalles, Oreg., was graduated from the University of Oregon in 1893 and from Massachusetts Institute of Technology in 1898. He remained as instructor at the University of Oregon, Eugene in 1893. During 1898 and 1899 he was employed variously as assistant in construction and installation for the Boston (Mass.) Electric Light Company in street surveying and construction for the Edison Electric Illuminating Company, Boston; and as inspector for the United States Corps of Engineers, Portland, Me. He returned to the Edison Illuminating Company in 1900 as assistant in design and equipment work and in 1901 was employed as draftsman by the New England Structural Company, Boston. In 1902 he joined the General Electric Company and remained in the company's district office at Boston until 1912. At different times during this period he had charge of drafting and designing and construction, wiring, and installation estimates. In 1913 he became professor of electrical engineering at Delaware College, Newark, and engineer for the Edison Storage Battery Company, Orange, N. J. In 1914 he was made assistant electrical engineer with the Interborough Rapid Transit Company, New York, N. Y. In 1917 he entered the Bureau of Yards and Docks, Navy Department, Washington, D. C., and except for a period in 1919 with the Bureau of Standards in Washington, remained with the Navy Department as electrical engineer until 1925. In 1926 he was made associate engineer in the supervising architect office, mechanical engineering division, Treasury Department, Washington, and in 1933 was transferred to the procurement division of the Treasury Department. He retired in 1937.

Frederick Dwight Nims (A '07, F '12) operating consultant and evaluation engineer, South Carolina Public Service Authority, Charleston, died March 2, 1944. Mr. Nims, who was born March 7, 1877, in Muskegon, Mich., commenced his career with the Muskegon Electric Light Company and the Muskegon Railway Company by which he was employed from 1894 to 1902 in various electrical positions and finally as superintendent. He was employed by the Utah Light and Railway Company, Salt Lake City, from 1902 to 1905 as division operating engineer, and in 1905 he joined the Mexico Light and Power Company, Mexico City, D. F., as chief operating engineer. From 1910 to 1914 he was associated with the Western Canada Power Company, Vancouver, B. C., as electrical engineer and general superintendent. He was assistant general manager and engineer for the Olympic Power Company, Port Angeles, Wash., from 1914 to 1916, becoming consulting engineer of the Olympic company in the latter year as well as general manager for the Washington Coast Utilities, Arlington. In 1917 he added the vice-presidency of the Washington Coast Utilities to his

duties. He was director of Parsons, Todd and Company, Boston, Mass., from 1924 to 1930. In 1925 he was president of the New Hampshire Power Company, Boston, and in 1926 was appointed receiver for the Hortonia Power Company, Rutland, Vt. He returned to Mexico as division manager of the Central Mexico Light and Power Company, Irapuato, Guan., in 1930 and remained there until 1938 when he was appointed senior engineer with the Public Works Administration, Washington, D. C. He had been with the South Carolina Public Service Authority since 1940. Mr. Nims served on the AIEE Sections committee for 1914–15 and on the committee on transmission and distribution for 1914–16.

Christian Julius Larsen (A '14, F '29) transmission engineer, Automatic Electric Company, Chicago, Ill., died February 7, 1944. Mr. Larsen was born in Copenhagen, Denmark, July 13, 1876, and received the degree of bachelor of science in engineering from the Lewis Institute of Science and Technology. In 1926 he was awarded the degree of doctor of science by Kansas City University. From 1909 to 1912 he was superintendent of equipment for the American Union Telephone Company, Harrisburg, Pa., and in 1912 when the Consolidated Telephone Company separated from the American Union, he became chief engineer for the Consolidated company. In 1915 he joined the Kansas City (Mo.) Home Telephone Company, serving as transmission engineer and superintendent of equipment and maintenance until 1919. In 1919 the Kansas City company merged with the Southwestern Bell Telephone Company and Mr. Larsen became building and equipment engineer for the combined companies. In 1925 he went abroad to make a study of automatic telephone systems in Belgium, Germany, and Sweden. Returning from Europe he was assigned in 1926 to a study of the telephone potentialities of South America. Later he supervised the automatic conversion of the telephone system in Caracas, Venezuela, and served as construction engineer in Barranquilla, Columbia. In 1929 he was appointed consulting engineer to the Associated Telephone and Telegraph Company, National Telephone and Telegraph Corporation, American Electric Company, Inc., and the Automatic Electric Company, Inc. Since 1931 he had been consultant on transmission problems to the Automatic Electric Company. Mr. Larsen served on the AIEE committee on communication from 1931 to 1935 and was a life member of the Telephone Pioneers of America.

George Barnett Smith (A '12, M '13) operating superintendent, eastern Ontario system, Hydro-Electric Power Commission of Ontario, Belleville, died December 10, 1943. Born August 18, 1876, in Wolverhampton, Staffordshire, England, Mr. Smith attended McGill University. In 1901 he entered the test department of the Royal Electric Company, Montreal, Que., and later that year the test department of the Lachine Rapids Hydraulic Land and Power Company, Montreal. From 1903 to 1909 he was associated with the Montreal Light, Heat and Power Company, in the test and meter department, the construction department, and the operating department, and was finally placed in charge of the construction department. In 1909 he joined Smith, Kerry and Chace, Consulting Engineers, Toronto, Ont., and in 1910 the Electric Power Company, Belleville, Ont., as general superintendent of the electrical department. Since 1917 he had been connected with the Hydro-Electric Power Commission of Ontario, Belleville, becoming district superintendent in 1922 and superintendent of the central Ontario system in 1925. He was made district operating superintendent in 1929 and superintendent of the eastern Ontario system in 1930. In 1937 he became operating superintendent.

William J. Davis, Jr. (A '95, M '12) retired consulting engineer, General Electric Company, Schenectady, N. Y., died February 18, 1944. Mr. Davis was born May 13, 1868, in Louisville, Ky., and was graduated from Rose Polytechnic Institute in 1892. He entered the employ of the General Electric Company, Lynn, Mass., in 1892 and was later transferred to Schenectady. He was engaged in testing, design, and construction until 1896 in which year he entered the railway engineering department. While in that department he did special engineering work in connection with the Detroit River Tunnel electrification and the electrificaton of the New York Central, and the West Jersey and Seashore, railway systems. He introduced forced ventilation for railway motors and made a pioneer study of train resistance. He was associated for a time with C. P. Steinmetz. From 1908 to 1921 he served as engineer in San Francisco, Calif., for the Pacific Coast district. For a part of this time he was chief engineer of the Mexican Northern Power Company. In 1921 he returned to the railway engineering department at Schenectady and when that department became the transportation engineering department in 1929 he was named consulting engineer. Mr. Davis retired in 1930.

Fred L. Hunt (A '05, F '17) vice-president in charge of operations, Western Massachusetts Companies, Greenfield, died February 8, 1944. Mr. Hunt, who was born in Delta, Iowa, August 4, 1879, received the degree of bachelor of science in electrical engineering from the University of Nebraska in 1902. He was employed in the testing department of the General Electric Company, Schenectady, N. Y., from 1902 to 1905 and in the latter year was transferred to the company's Boston, Mass., office as trouble man, later becoming assistant district engineer. In 1913 he was made chief engineer of the Turner Falls Power and Electric Company, Greenfield, and allied companies and was simultaneously general manager of the Connecticut River Conservation Company. In 1927 he was appointed director of economics and engineering of the Western Massachusetts Companies and in 1937 was elected vice-president. Mr. Hunt was a member of the following AIEE committees: protective devices, 1914–16, 1919–24, 1927–29; Standards, 1923–24, 1927–32; meetings and papers, 1926–28. He was the author of several technical papers and president of the Engineering Society of Western Massachusetts. Mr. Hunt also served on several technical committees of the National Electric Light Association.

Edward Hotchkiss Everit (A '02, F '12) retired assistant to the general manager of the Southern New England Telephone Company, New Haven, Conn., died October 5, 1943. He was born August 5, 1870, in New Haven and attended Columbia University. Mr. Everit's entire career, which commenced when in 1889 he entered the equipment maintenance department of the Southern New England company, was spent in the field of communication engineering. He became superintendent of equipment in 1897, engineer in 1903, and chief engineer in 1910. He was appointed assistant to the general manager in 1927 and retired in 1931. Active in Institute affairs, he was chairman of the Connecticut Section from 1922 to 1924, a member of the committee on communications from 1925 to 1930, and a member of the board of examiners from 1922 to 1930 and chairman from 1927 to 1930. He also was a member of the American Society for the Advancement of Science, the American and Connecticut Forestry Associations, the Connecticut Society of Civil Engineers, the New York Electrical Society, the Society for the Promotion of Engineering Education, and the Telephone Pioneers of America.

Newton Stout Taylor (A '14, M '26) manager of switchgear order service department, Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa., died February 21, 1944. Born in Lancaster, Ky., November 11, 1888, Mr. Taylor was graduated from the University of Kentucky in 1909. He entered the apprenticeship course of the Westinghouse company in 1909 and in 1911 was made switchboard specialist in the company's Denver, Colo., office. Returning to East Pittsburgh in 1915 he continued as switchboard specialist until 1920. In 1918 he was responsible for all work with the government in connection with battleships, navy yards, and ordnance plants. He was made acting manager of the switchboard section in 1920 and manager in 1925. In 1933 he was appointed manager of switchgear apparatus and in 1939 supervisor of the switchgear order service. Since 1940 he had been manager of the switchgear order service. Mr. Taylor was awarded the Westinghouse order of merit for his outstanding work in speeding delivery of equipment to the United States Navy and war industries.

William Beckett (M '26) design engineer, Georgia Power Company, Atlanta, died December 11, 1943. Born August 26, 1886, in Charleston, S. C., Mr. Beckett was graduated from Clemson College with the degree of bachelor of science in electrical engineering in 1906. During 1906 and 1907 he was employed in the testing department of the General Electric Company, Schenectady, N. Y. He entered the drafting department of the Public Service Electric Company, Newark, N. J., and in 1911 was transferred to the construction department as foreman on installation of substation equipment. From 1913 to 1917 he was general foreman of construction for the Carolina

Power and Light Company, Raleigh, N. C. In 1917 he joined the Georgia Railway and Power Company, which later became the Georgia Power Company, as draftsman and in 1918 became chief draftsman. From 1919 to 1922 he worked for Lockwood, Greene and Company, Atlanta, as designer. He returned to the Georgia Power Company in 1922 as design engineer and had been associated with that company since.

Ford DeCamp Thompson (A '07) retired supplies inspection superintendent, Western Electric Company, Inc., died February 3, 1944. He was born March 1, 1878, in Detroit, Mich., and first joined the Western Electric Company, New York, N. Y., in 1896. In 1898 and 1899 during the Spanish-American War he served in the Signal Corps of the United States Army. Returning to the Western Electric Company in 1899 he was placed in charge of inspecting and testing of manufactured apparatus. In 1904 he entered the engineering department to work on general apparatus inspection and in 1906 inspection of supplies for the telephone companies was added to his duties. During the next decade he helped organize repair shops and standardize repair methods and engineering inspection throughout the American Bell System. In 1919 he was named supplies inspection superintendent and in 1943 he retired.

Elmer Ellsworth Boyer (A '95, F '12) retired engineer, General Electric Company, Lynn, Mass., died February 9, 1944. He was born July 23, 1861, in Sunbury, Pa., and attended Hobart College and Lehigh University. From 1880 to 1885 he worked in the machine shops of the Pennsylvania Railroad, Sunbury, and in 1885 entered the testing department of the Thomson–Houston Company, Lynn, Mass. About 1900 he became foreman of the testing department of the General Electric Company at Lynn. In 1911 he was transferred to West Lynn, Mass., as electrical superintendent and remained in that position until 1922 when he was appointed head of the industrial service department. He retired in 1930. He was associated with such electrical pioneers as Elihu Thomson, E. W. Rice, Jr., and C. P. Steinmetz.

Charles Paul Rhine (A '18) division maintenance engineer, San Joaquin power division, Pacific Gas and Electric Company, Fresno, Calif., died January 17, 1944. Mr. Rhine was born in New Castle, Ind., November 9, 1883, and was graduated from Purdue University in 1909. He commenced his career as electrical draftsman in the signal department of the Southern Pacific Company, San Francisco, Calif., in 1909. In 1918 he joined the San Joaquin Light and Power Corporation, Fresno. He was named construction engineer in 1920, mechanical engineer in 1924, and electrical engineer in 1927. After a year as resident engineer in the San Francisco steam plant of the Great Western Power Company in 1928 he returned to the San Joaquin Corporation and had been with the San Joaquin division of the Pacific Gas and Electric Company since 1940. He was a member of the Pacific Coast Electrical Association.

Harry Molyneux King (M '21) operating superintendent, Ontario Power Plant, Hydro-Electric Power Commission of Ontario, Niagara Falls, died December 6, 1943. Mr. King was born September 12, 1877, in Brooklyn, N. Y. He commenced his career as a journeyman for an electrical contractor in Providence, R. I., and in 1903 was engaged by the Narragansett Electric Lighting Company, Providence, for substation and other construction. From 1906 to 1910 he erected apparatus for the Westinghouse Electric and Manufacturing Company, Buffalo, N. Y. He joined the Ontario Power Company, Niagara Falls, as electrical supervisor in 1910 and became operating superintendent in 1923. When the company was taken over by the Hydro-Electric Power Commission of Ontario in 1924, he continued in that position.

Weldon O. Hampton (M '41) chief design engineer, Delta-Star Electric Company, Chicago, Ill., died February 9, 1944. Mr. Hampton, who was born June 21, 1902, in Fort Smith, Ark., commenced his career in the machine shop of the Victor Electric Corporation, Chicago, in 1917. From 1918 to 1922 he worked as draftsman for the Automatic Electric Company, Chicago, and in 1922 joined the Delta-Star company as engineering draftsman. In 1926 he was made field engineer and head of standardization and in 1929 became head of the patent department. He was appointed assistant to the chief engineer in 1933, assistant chief engineer in 1937, and chief design engineer in 1941.

MEMBERSHIP

Recommended for Transfer

The board of examiners at its meeting on March 16, 1944, recommended the following members for transfer to the grade of membership indicated. Any objection to these transfers should be filed at once with the national secretary.

To Grade of Fellow

Crittenden, E. C., chief, electrical division and assistant director, National Bureau of Standards, Washington, D. C.
Deakin, Gerald, vice-president & general technical director, I. T. & T. and Int'l. Standard Elec. Corp., New York.
DeLanty, B. F., general manager & electrical engr., Light and Power Dept., City of Pasadena, Calif.
Hooven, M. D., elec. engr., Public Service Electric & Gas Co., Newark, N. J.
Lovell, C. M., vice-president & chief engr., Moloney Electric Co., St. Louis, Mo.
Mullen, J. J., president, Moloney Electric Co., St. Louis, Mo.
Stevens, F. J., vice-president, Engg., American Lava Corp., Chattanooga, Tenn.
Ware, J. S., general supt. of distribution, Public Service Elec. & Gas Co., Newark, N. J.

8 to grade of Fellow

To Grade of Member

Aster, A. K., engr., Westinghouse Electric Elevator Co., Jersey City, N. J.
Bailey, R. E., senior elec. engr., Tennessee Eastman Corp., Oak Ridge, Tenn.
Ballard, B. G., head of elec. engg. section, National Research Council of Canada, Ottawa, Canada.
Behrens, W. J., starting engr., S.G., Commonwealth Edison Co., Chicago, Ill.
Dandeno, G. G., supt., Thunder Bay System, Hydro-electric Power Comm., Cameron Falls, Ont., Canada.
Darrah, M. D., chief elec. engr., The Austin Co., Dallas, Texas.
d'Eois, F. B., R.N.V.R., S.A.V.S., South Africa House, London, England.
Denison, H. C., elec. engr., Oklahoma Gas & Elec. Co., Oklahoma City, Okla.
Fosnick, J. F., Underground engr., Memphis Light, Gas & Water Division, Memphis, Tenn.
Frolich, J. F., designing engr. Sanderson & Porter, New York.
Gentry, P. E., division plant engr., Southwestern Bel Tel. Co., Tulsa, Okla.
Glick, H. S., elec. engr., Holston Ordnance Works, Tennessee Eastman Corp., Kingsport, Tenn.
Goldberg, Harold, senior engr., Research Dept., Stromberg-Carlson Co., Rochester, N. Y.
Hall, J. E., assistant supt. of distribution, Blackstone Valley Gas & Elec. Co., Pawtucket, R. I.
Horsfall, W. H. D., works mgr. Canada Wire & Cable Co. Ltd., Toronto, Canada.
Hughes, P. H., engr., New Jersey Bell Tel. Co., Newark, N. J.
Hunt, R. W., elec. supt., Keene District, Public Service Co. of New Hampshire, Keene, N. H.
Irey, G. W., supt. of generating stations, The Empire District Elec. Co., Joplin, Mo.
Jett, C. O., chief elec. engr., Atlas Powder Co., Paducah, Ky.
Kooker, E. M., elec. engr., General Electric Co., Cleveland, Ohio.
Lamb, F. X., Division chief, Weston Electrical Instrument Corp., Newark, N. J.
Limpel, E. J., supervisor of elec. research lab., A. O. Smith Corp., Milwaukee, Wis.
Marks, L. W., development engr., General Electric Co., Pittsfield, Mass.
Maxcy, David, assistant elec. engr., Sanderson & Porter, New York.
Menendez, R. A., elec. engr., Tampa Armature Works, Tampa, Fla.
Messinger, L. E., president, managing director, Canadian Line Materials, Ltd., Toronto, Canada.
Nordquist, C. A., district mgr., Railway & Industrial Engg. Co., Chicago, Ill.
Pickering, A. E., vice-president and general mgr., Great Lakes Power Co. Ltd., Sault Ste. Marie, Ont., Canada.
Scott, W. K., asst. elec. supt., Columbia Steel Co., Pittsburg, Calif.
Sepmeyer, L. W., associate engr., Univ. of Calif. Div. War Research, San Diego, Calif.
Thwaites, J. T., section engr., Canada Westinghouse Co., Hamilton, Canada.
Tilton, R. G., engr. and expeditor, Otis Elevator Co., New York.
Trevett, H. N., associate prof. of elec. eng., Rensselaer Polytechnic Institute, Troy, N. Y.
Van Zeeland, F. J., dean and professor of elec. engg., Milwaukee School of Engg., Milwaukee, Wis.
Veverka, Frank, Elec. engr., Central Hudson Gas & Elec. Corp., Poughkeepsie, N. Y.
Walker, W. W., general mgr., Graphite Metallising Corp., Yonkers, N. Y.
Wold, T., chief engr., Smith & Stone, Ltd., Georgetown, Ont., Canada.

37 to grade of Member

Applications for Election

Applications have been received at headquarters from the following candidates for election to membership in the Institute. Names of applicants in the United States and Canada are arranged by geographical District. Any member objecting to the election of any of these candidates should so inform the national secretary before April 30, 1944, or June 30, 1944, if the applicant resides outside of the United States or Canada.

To Grade of Member

Balogh, S. I., Solar Mfg. Co., Bayonne, N. J.
Beaty, H. C., Southeastern Shipbuilding Corp., Savannah, Ga.
Beebe, H. D., Tampa Elec. Co., Tampa, Fla.
Bowen, J. B., San Diego Gas & Elec. Co., San Diego, Calif.
Bruns, W. H. (Re-election), Otis Elevator Co., New York, N. Y.
Clarbonneau, A. P., Cutler Hammer, Inc., Milwaukee, Wis.
Coulomb, C. A., Jr., American Tel. & Tel. Co., Philadelphia, Pa.
Cronemiller, G. D., U. S. Maritime Comm., Portland, Oreg.
Crook, R. A., Alan Crook Electrical Co. Pty. Ltd., St. Leonards, Aust.
Davis, G. R., Hydro Electric Comm., Ottawa, Ont., Can.
Day, W. L. G., Lockheed Aircraft Corp., Burbank, Calif.
Dunsmoor, R. W., Webster Brinkley Co., Seattle, Wash.
Fenn, W. D., Simplex Wire & Cable Co., Cambridge, Mass.
Fox, H., General Elec. Co., Boston, Mass.
Hall, T. L., Public Service Elect. & Gas Co., Irvington, N. J.
Hare, R. J. (Re-election), Southern Calif. Tel. Co., Los Angeles, Calif.
Harrigan, M. A. P., Lieut., R.C.N.V.R., Halifax, N. S., Can.
Hassell, H. M., Demerara Elec. Co., Ltd., Georgetown, British Guiana, S. A.
Henry, E. B., Commonwealth & Southern Corp., Birmingham, Ala.
Hughes, H. D., Frick-Reid Supply Corp., Tulsa, Okla.
Johnson, E. M., General Electric Co., Seattle, Wash.
Kachni, F. J., Kachni Bros. Laboratory, Cleveland, Ohio.
Kachni, W. L., Kachni Bros. Laboratory, Cleveland, Ohio.
Kime, R. R. (Re-election), Sales Engineer, 40 Wall St., New York, N. Y.
Kirkpatrick, C. M. (Re-election), Westinghouse Elec. & Mfg. Co., New York, N. Y.
Lasgdon, G. G. (Re-election), American Gas & Elec. Service Corp., New York, N. Y.

Miller, H. P., Jr. (Re-election), Federal Tel. & Radio Corp., Newark, N. J.
Parker, R., Electricity Commisson, London, England.
Peters, K. O., Bureau of Standards, Washington, D. C.
Peterson, E. G. (Re-election), Cutler-Hammer, Inc., Milwaukee, Wis.
Povey, E. H., Doble Engineering Co., Medford, Mass.
Pullen, F. C., Tenn. Eastman Corp., Knoxville, Tenn.
Richards, R., Electrical Contractor, Carrollton, Ga.
Rowland, G. W., James R. Kearney Corp., St. Louis, Mo.
Settles, O. P., Mountain States Tel. & Tel. Co., Denver, Colo.
Skaale, A. J., Carolina Pwr. & Lt. Co., Raleigh, N. C.
Smith, G. D., Todd Shipyards Corp., Brooklyn, N. Y.
Tally, O. V., Allis-Chalmers Mfg. Co., St. Louis, Mo.
Walker, F. H., Bell Aircraft Corp., Niagara Falls, N. Y.
Whitesell, R. O., P. R. Mallory & Co., Indianapolis, Ind.
Wolstenholme, P. G., Aluminum Co. of Can., Ltd., LaTuque, Que., Can.
Zimmerman, D. L., Zimmerman Elec. Mchry. Co., Wichita, Kans.

42 to grade of Member

To Grade of Associate

United States and Canada

1. North Eastern

Aguilar, J. R., General Elec. Co., Schenectady, N. Y.
Ahrens, J. H. (Re-election), Hartford Elec. Light Co., Hartford, Conn.
Alexander, D. C., Worcester Poly. Inst., Worcester, Mass.
Anderson, W. T., Gen. Elec. Co., Schenectady, N. Y.
Arana, M. O., Int. General Elec. Co., Schenectady, N. Y.
Aude, J. R., General Elec. Co., Schenectady, N. Y.
Baird, G. A., General Elec. Co., Schenectady, N. Y.
Bludeau, R. E., Linde Air Products Lab., Tonawanda, N. Y.
Brockman, M. H., Harvard Univ., Cambridge, Mass.
Buell, L. V., Spencer Thermostat Co., Attleboro, Mass.
Buffinton, R. B., General Elec. Co., Boston, Mass.
Bunger, J. W., General Elec. Co., Schenectady, N. Y.
Burks, J. O., Jr., Univ. of Conn., Storrs, Conn.
Butler, C. S., Jr., Abbott Associates, Hartford, Conn.
Cain, D. E., General Elec. Co., Schenectady, N. Y.
Capehart, D. F., General Elec. Co., Pittsfield, Mass.
Champlin, F., Jr., USMCR, Dalton, Mass.
Cohen, S., Mass. Inst. of Tech., Cambridge, Mass.
Coolidge, J. E., Jr., General Elec. Co., Schenectady, N. Y.
DeLuca, F. C., Landers, Frary & Clark, New Britain, Conn.
Epping, F. J., Bausch & Lomb Optical Co., Rochester, N. Y.
Escalante, G. A., General Elec. Co., Lynn, Mass.
Franke, D. A., General Elec. Co., Schenectady, N. Y.
Fulton, R. W., Factory Insurance Association, Syracuse, N. Y.
Gove, I. N., Univ. of Conn., Storrs, Conn.
Hammerstein, E. H., General Elec. Co., Schenectady, N. Y.
Hammett, R. L., Harvard Univ., Cambridge, Mass.
Hanna, R. L., General Elec. Co., Syracuse, N. Y.
Harold, R. D., General Elec. Co., Schenectady, N. Y.
Hartl, M. E., General Elec. Co., Schenectady, N. Y.
Hochgesang, C. F., General Elec. Co., Schenectady, N. Y.
Hodgers, R. W., Jr., General Elec. Co., Schenectady, N. Y.
Hotze, I. A., General Elec. Co., Schenectady, N. Y.
Howard, W. M., Westinghouse Elec. & Mfg. Co., South Boston, Mass.
Hubley, F. N., Westinghouse Elec. & Mfg. Co., Boston, Mass.
Isaak, R. D., General Elec. Co., Schenectady, N. Y.
Jasper, R. N., General Elec. Co., Schenectady, N. Y.
Jensen, E. M., General Elec. Co., Schenectady, N. Y.
Jones, A. B., Boston Edison Co., Boston, Mass.
Kroener, J. T., Columbia Univ. Div. of War Res., New London, Conn.
Leigh, C. T., New Bedford Rayon Co., New Bedford, Mass.
Loudon, J. J. M., General Elec. Co., Schenectady, N. Y.
Loughran, J. A., General Elec. Co., Schenectady, N. Y.
MacFee, F. O., Jr., General Elec. Co., Lynn, Mass.
Maier, R. V., General Elec. Co., Syracuse, N. Y.
Mather, D. L., General Elec. Co., Schenectady, N. Y.
Mathews, C. G., General Elec. Co., Schenectady, N. Y.
Moore, R. A., General Elec. Co., Schenectady, N. Y.
Motter, D. P., General Electric Co., Schenectady, N. Y.
O'Keefe, J. B., Electro Metallurgical Co., Niagara Falls, N. Y.
Ottens, R. C., Mass. Inst. of Tech., Cambridge, Mass.
Palmer, R. C., General Elec. Co., Schenectady, N. Y.
Patridge, L. F., E. B. Badger & Sons Co., Boston, Mass.
Peebles, J. E., General Elec. Co., Schenectady, N. Y.
Perron, R. K., Sylvania Elec. Prod. Co., Inc., Salem, Mass.
Petrich, R. O., Harvard Univ., Cambridge, Mass.
Putman, J. L. (Re-election), American Bosch Corp., Springfield, Mass.
Reed, H. J., Mass. Inst. of Tech., Cambridge, Mass.
Renner, G. W., Harvard Univ., Cambridge, Mass.
Reuter, J. M., Chance Vought Aircraft, Stratford, Conn.
Roberts, E. W., Conn. Light & Power Co., Waterbury, Conn.
Rodrigues, M. F., General Elec. Co., Schenectady, N. Y.
Schick, R. A., General Elec. Co., Fitchburg, Mass.
Setsco, J. E., General Elec. Co., Schenectady, N. Y.
Sibary, T. W., General Elec. Co., Schenectady, N. Y.
Spencer, W. B., General Elec. Co., Schenectady, N. Y.
Stannard, G. E., Mass. Inst. Tech., Cambridge, Mass.
Tallman, B. D., Curtiss Wright Corp., Buffalo, N. Y.
TeWinkle, G. J., Niag. Lockport & Ont. Pr. Co., Medina, N. Y.
Thomsen, J. S., General Elec. Co., Schenectady, N. Y.
Thuma, T. E., General Elec. Co., Schenectady, N. Y.
Thwing, S. G., General Elec. Co., West Lynn, Mass.
Tomcik, D. J., General Elec. Co., Schenectady, N. Y.
Trembley, H. G., General Elec. Co., Lynn, Mass.
Trembly, G. C., Mass. Inst. of Tech., Cambridge, Mass.
Tunnicliffe, W. W., Mass. Inst. of Tech., Cambridge, Mass.
Twyford, L. C., Jr., General Elec. Co., Schenectady, N. Y.
Wahl, N. W., New York State Elec. & Gas Corp., Lockport, N. Y.
Wheeler, D. B., General Elec. Co., Schenectady, N. Y.
Whipple, D. C., General Elec. Co., Schenectady, N. Y.
White, R. F., General Elec. Co., Schenectady, N. Y.
Wholey, W. B., Harvard Univ., Cambridge, Mass.
Williams, A. J., General Railway Signal Co., Rochester, N. Y.
Wilson, R. D., Mass. Inst. of Tech., Boston, Mass.
Wohlt, W. F., Jr., General Elec. Co., Pittsfield, Mass.
Woodruff, T. E., General Elec. Co., Syracuse, N. Y.
Vaughan, V. G., Spencer Thermostat Co., Attleboro, Mass.
Young, R. H., General Elec. Co., Syracuse, N. Y.
Zaskalicky, J. J., General Elec. Co., Schenectady, N. Y.

2. Middle Eastern

Allen, W. W., Jr., Naval Research Lab., Washington, D. C.
Asbury, A., Westinghouse Elec. & Mfg. Co., East Pittsburgh, Pa.
Atkinson, J. R., Naval Research Lab., Washington, D. C.
Babcox, R. H., Jr., American Shipbuilding Co., Lorain, Ohio.
Banks, J., U. S. Navy Yard, Philadelphia, Pa.
Barr, H. V., Ohio Power Co., Philo, Ohio.
Bissell, E. E., Jr., Naval Research Lab., Washington, D. C.
Boothroyd, R. L., General Elec. Co., Erie, Pa.
Carlstrom, T. H., Sylvania Elec. Prod., Inc., Emporium, Pa.
Cronenberger, H. G., Alum. Co. of America, Burlington, N. J.
DeJong, P. G., Naval Ordnance Lab., Washington, D. C.
Deming, A. S., Jr., U. S. Navy Dept., Washington, D. C.
Dewey, R. M., West Penn Power Co., Connellsville, Pa.
Dobler, L. R., Naval Research Lab., Washington, D. C.
Dominick, J. W., Phila. Elec. Co., Philadelphia, Pa.
Duck, L. P., Philadelphia Signal Corps, Philadelphia, Pa.
Duckwall, R. H., Frigidaire Corp., Dayton, Ohio.
Dunn, T. E., Victor Div., Radio Corp. of Amer., Camden, N. J.
Dykes, W. W., General Elec. Co., Philadelphia, Pa.
Gallagher, W. M., Ohio Bell Telephone Co., Dayton, Ohio.
Gilman, F. L., Westinghouse Elec. & Mfg. Co., East Pittsburgh, Pa.
Glass, W. L., General Elec. Co., Philadelphia, Pa.
Goodman, H. A., Philco Corp., Philadelphia, Pa.
Gruber, J. R., Naval Research Lab., Washington, D. C.
Hageman, K. G., Naval Research Lab., Washington, D. C.
Hagemack, C. G., Westinghouse Elec. & Mfg. Co., East Pittsburgh, Pa.
Hager, W. J., Jr., Westinghouse Elec. & Mfg. Co., Toledo, Ohio.
Hancock, H. A., Univ. of Cincinnati, Cincinnati, Ohio.
Hand, R. C., Reliance Elec. & Engg. Co., Cleveland, Ohio.
Hanlon, R. P., SKF Industries, Inc., Philadelphia, Pa.
Hawthorne, E. I., Victor Div., Radio Corp. of America, Camden, N. J.
Henncay, R. G., Naval Research Lab., Washington, D. C.
Hill, V. E. (Re-election), Duquesne Light Co., Pittsburgh, Pa.
Houston, R. H., Naval Research Lab., Washington, D. C.
Hubbard, L. H., Jr., Westinghouse Elec. & Mfg. Co., East Pittsburgh, Pa.
Kelly, R. S., Naval Research Lab., Washington, D. C.
Knowles, R. B., Naval Ordnance Lab., Washington, D. C.
Koenig, E., Allis-Chalmers Mfg. Co., Norwood, Ohio.
Kroner, J., Jr., Alum. Co. of America, Burlington, N. J.
Kunz, C. G., Jr., Sylvania Elec. Prod., Inc., Williamsport, Pa.
Lawrence, R. F., Westinghouse Elec. & Mfg. Co., East Pittsburgh, Pa.
Leedom, D. N., Naval Research Lab., Washington, D. C.
Leslie, C. B., Naval Ordnance Lab., Washington, D. C.
Leslie, F. A. (Re-election), Cons. Gas Elec. Lt. & Pwr. Co. of Baltimore, Baltimore, Md.
Lindsay, R. W., Westinghouse Elec. & Mfg. Co., East Pittsburgh, Pa.
Livensparger, R. B., Westinghouse Elec. & Mfg. Co., Baltimore, Md.
Locus, S. S., Westinghouse Elec. & Mfg. Co., East Pittsburgh, Pa.
Markle, L. E. (Re-election), Westinghouse Elec. & Mfg. Co., East Pittsburgh, Pa.
Metz, W. L., Westinghouse Elec. & Mfg. Co., East Pittsburgh, Pa.
Michael, F. R., Univ. of Penn., Philadelphia, Pa.
Morris, J., Princeton Univ., Princeton, N. J.
Myers, D. K., Westinghouse Elec. & Mfg. Co., East Pittsburgh, Pa.
Myers, J. D., Westinghouse Elec. & Mfg. Co., East Pittsburgh, Pa.
Newborg, D. S., Victor Div., Radio Corp. of America, Camden, N. J.
Oprendek, F., Electric Serv. Supplies Co., Pittsburgh, Pa.
Oras, R., Naval Research Lab., Washington, D. C.
Pereira, S. R., Inter-American Trade Scholarship, Washington, D. C.
Peterson, R. E., Naval Research Lab., Washington, D. C.
Phelan, R. F., Lear Avia, Inc., Piqua, Ohio.
Polstein, M., Westinghouse Elec. & Mfg. Co., East Pittsburgh, Pa.
Rath, H. B., Mack Mfg. Corp., Allentown, Pa.
Ray, W. C., Goodyear Tire & Rubber Co., Akron, Ohio.
Rennie, W. A., American Shipbuilding Co., Lorain, Ohio.
Riley, R. N., Westinghouse Elec. & Mfg. Co., Baltimore, Md.
Robinson, J. G., Princeton Univ., Princeton, N. J.
Rosenthal, L., Lehigh Univ., Bethlehem, Pa.
Rydbeck, V. A., General Elec. Co., Erie, Pa.
Schaedler, T. J., Phila. Signal Corps Procurement Dist., Philadelphia, Pa.
Schaefer, E. J., National Defense Res. Comm., Princeton, N. J.
Schmeizer, J. W., Westinghouse Elec. & Mfg. Co., East Pittsburgh, Pa.
Schmidt, D. W., Westinghouse Elec. & Mfg. Co., Lima, Ohio
Schultz, A. J., Sylvania Elec. Prod., Inc., Emporium, Pa.
Shankle, D. F., Westinghouse Elec. & Mfg. Co., East Pittsburgh, Pa.
Shefter, J. F. G., Bethlehem Steel Co., Williamsport, Pa.
Stuart, M. J., General Elec. Co., Philadelphia, Pa.
Thompson, D. C., Pesco Products Co., Cleveland, Ohio.
Troxel, D. L., Naval Research Lab., Washington, D. C.
Venturine, J. B., Elliott Co., Jeannette, Pa.
Verduin, L. C., U. S. Naval Ord. Lab., Washington, D. C.
Watkins, J. E., Bureau of Ships, Washington, D. C.
Webb, C. W., Naval Research Lab., Washington, D. C.
Weber, W. H., Naval Research Lab., Washington, D. C.
Wuerffel, H. L., Naval Research Lab., Washington, D. C.
Yinger, L. K., Metropolitan Edison Co., York Haven, Pa.

3. New York City

Anderson, J. R., Bendix Aviation Corp., Bendix, N. J.
Baehr, W. H., Arma Corp., Brooklyn, N. Y.
Barrett, A. G., Federal Tel. & Radio Corp., New York, N. Y.
Beebe, L. E., Curtiss-Wright Corp., Caldwell, N. J.
Berg, A., Consolidated Diesel Electric Corp., New York, N. Y.
Black, R. W., Conlan Elec. Corp., Brooklyn, N. Y.
Blake, J. J. H., Western Elec. Co., New York, N. Y.
Botwin, L., Bendix Avia. Corp., Brooklyn, N. Y.
Boyd, R. H., Pennsylvania R.R. Co., New York, N. Y.
Bradburd, E. M., Federal Tel. & Radio Labs., New York, N. Y.
Brecht, A. J., Arma Corporation, Brooklyn, N. Y.
Bregar, J. C., Western Elec. Co., New York, N. Y.
Brose, R. B., Diehl Mfg. Co., Somerville, N. J.
Buckwalter, K., U. S. Army, Ft. Monmouth, N. J.
Burns, A. E. (Re-election), 1958 E. 29th St., Brooklyn, N. Y.
Cataldo, J., Pierce Laboratory, Inc., Summit, N. J.
Champion, C. E., Western Elec. Co., Inc., Kearny, N. J.
Chardon, R. C., Puerto Rico Water Resources Auth., Guayama, P. R.
Charlton, J., Sperry Gyroscope Co. Inc., Brooklyn, N. Y.
Clark, M. R., U. S. Army, Ft. Monmouth, N. J.
Clark, W. M., Sperry Products, Inc., Hoboken, N. J.
Coe, M. R., Electricoil Transformer Co., New York, N. Y.
Cohen, N. L., Federal Tel. & Radio Labs., New York, N. Y.
Cox, J. W., Federal Tel. & Radio Corp., Newark, N. J.
Danbeck, F. S., Public Serv. Elec. & Gas Co., Irvington, N. J.
Drummond, W. F., Otis Elevator Co., Yonkers, N. Y.
Ehrhardt, E. J., Federal Tel. & Radio Corp., Newark, N. J.
Eubank, H. S., Poly. Inst. of Brooklyn, Brooklyn, N. Y.
Evans, W. E., Jr., Bell Tel. Labs., New York, N. Y.
Falk, H., Brooklyn Edison Co., Brooklyn, N. Y.
Figueroa, J., American R.R. Co. of P. R., San Juan, P. R.
Foster, W. P., General Cable Corp., Bayonne, N. J.
Frey, H. B., Jr., Western Elec. Co., Kearny, N. J.
Gilmartin, J. J., Jr., Sperry Gyroscope Co., Garden City, N. Y.
Goetchius, R. M., American Tel. & Tel. Co., New York, N. Y.
Goodman, D. M., Standard Aircraft Prod., Inc., New York, N. Y.
Goodman, P. D., Airborne Instrument Lab., Mineola, N. Y.
Goronin, A., Sperry Gyroscope Co., Inc., Lake Success, N. Y.
Grad, H., Westinghouse Elect. Elevator Co., Jersey City, N. J.
Greenberg, J., Federal Tel. & Radio Corp., New York, N. Y.
Gunmersall, J. R., Jefferson Travis Radio Mfg. Corp., New York, N. Y.
Hellman, H. I., Lummus Company, New York, N. Y.
Henches, E., N. Y. Tel. Co., New York, N. Y.
Houna, R. E., Curtiss-Wright Corp., Caldwell, N. J.
Huggins, C. E., Curtiss-Wright Corp., Caldwell, N. J.
Hyman, A., Micamold Radio Corp., Brooklyn, N. Y.
Just, G. A., Jr., Pan-American Grace Airways, New York, N. Y.
Kalning, W. C., Induction Heating Corp., New York, N. Y.
Kaplan, R., Electric Boat Co., Bayonne, N. J.
King, W. J., Bell Tel. Labs., Inc., New York, N. Y.
Koch, W. L., N. Y. Tel. Co., New York, N. Y.
Koskos, P., Western Electric Co., New York, N. Y.
Lacopo, M. J., American Gas & Elec. Serv. Corp., New York, N. Y.
Lautin, M. E., Davidson Electric Co., Brooklyn, N. Y.

Livingstone, T. A., Okonite Callender Cable Co., Inc., Paterson, N. J.
Madey, R., Allen B. DuMont Labs. Inc., Passaic, N. J.
Malone, J. J., Curtiss-Wright Corp., Caldwell, N. J.
Marcy, R. J., Federal Radio & Tel. Corp., Newark, N. J.
Margossian, J. W., Polytechnic Inst. of Brooklyn, Brooklyn, N. Y.
McIlveen, E. E., Okonite Cor., Passaic, N. J.
Meyer, B. C., Bell Tel. Labs., New York, N. Y.
Miller, B. E., Sperry Gyroscope Co., Garden City, N. Y.
Moffitt, A. B., American Tel. & Tel. Co., New York, N. Y.
Monahaw, J. H., Penn. R.R. Co., New York, N. Y.
Morales, D. J., Western Electric Co., New York, N. Y.
Mulligan, J. H., Jr., Bell Tel. Labs. Inc., New York, N. Y.
Mullin, V. E., Conlan Elec. Corp., Brooklyn, N. Y.
Nelson, G. L., Conlan Elec. Corp., Brooklyn, N. Y.
Ossmann, E. A., DuMont Labs., Inc., Clifton, N. J.
Owen, R. P., Allen B. DuMont Labs. Inc., Passaic, N. J.
Parsons, B. L., Sperry Gyroscope Co., Garden City, N. Y.
Piller, S. E., Radio Navigational Inst. Corp., New York, N. Y.
Plotkin, M., Bendix Aviation Corp., Brooklyn, N. Y.
Ranks, J. E., Westinghouse Elec. & Mfg. Co., Bloomfield, N. J.
Rigie, B., Bendix Avia. Corp., Brooklyn, N. Y.
Rossoll, A. L., Poly. Inst. of Brooklyn, Brooklyn, N. Y.
Rothstein, M., Federal Tel. & Radio Corp., Newark, N. J.
Rozolis, J., Fairchild Camera & Inst. Corp., New York, N. Y.
Sanflippo, N., Glidden Buick Corp., New York, N. Y.
Sauter, E. A., Teleregister Corp., New York, N. Y.
Segall, H., Radio Receptor Co., New York, N. Y.
Smart, T. E., Airborne Inst. Lab., Columbia Univ., Mineola, N. Y.
Smith, H. E. (Re-election), General Electric Co., Newark, N. J.
Stoker, F. E., U. S. Signal Corps, c/o Postmaster, New York, N. Y.
Strause, P. H., Victor Div. Radio Corp. of America, Harrison, N. J.
Talesnick, S., Radio Receptor Co. Inc., New York, N. Y.
Toppan, A. C., Fairchild Camera & Inst. Corp., New York, N. Y.
Totah, E. J., Communication Measurements Lab., New York, N. Y.
Turk, J., Federal Tel. & Radio Corp., New York, N. Y.
Urbandt, J. G., W. L. Maxson Corp., New York, N. Y.
Waas, A., Smith-Meeker Engg. Co., New York, N. Y.
Wheye, O. M., Columbia Univ., Mineola, N. Y.

4. Southern

Adkins, B. G., Water, Gas & Electric Dept., Danville, Va.
Becker, M. C., Tennessee Eastman Corp., Knoxville, Tenn.
Bright, J. W., Westinghouse Elec. Sup. Co., Norfolk, Va.
Bristol, H. C., Knoxville Power Co., Alcoa, Tenn.
Brown, F. P., Bechtel-McCone-Parsons Corp., Birmingham, Ala.
Campbell, J. S., Tennessee Eastman Corp., Oak Ridge, Tenn.
Dillard, E. G., Memphis Light Gas & Water Div., Memphis, Tenn.
Gerhart, F. A., Tennessee Eastman Corp., Oak Ridge, Tenn.
Grantham, L. F., Andrews Steel Co., Newport, Ky.
Harder, R. N., Alum. Co. of America, Alcoa, Tenn.
Herring, R. L., Southern Bell Tel. Co., Atlanta, Ga.
Holloway, C. F., Tennessee Eastman Corp., Knoxville, Tenn.
Hudson, E. D., Tennessee Eastman Corp., Knoxville, Tenn.
Humphrey, A. J., Alum. Co. of America, Alcoa, Tenn.
Hunt, J. W., Shelby Electric Co., Inc., Memphis, Tenn.
Jones, D. H., N.A.C.A., Langley Field, Va.
Khouri, A., Univ. of Fla., Gainesville, Fla.
Leder, W., U. S. Army, Daniel Field, Ga.
Less, E. M., Tennessee Eastman Corp., Oak Ridge, Tenn.
McDonough, J. O., 2nd Lt., U. S. Army, Ft. Belvoir, Va.
Robertson, D. A., Tennessee Eastman Corp., Oak Ridge, Tenn.
Stevenson, J. W., Tenn. Valley Auth., Chattanooga, Tenn.
Vanaman, L. J., Knoxville Elec. Pr. & Water Board, Knoxville, Tenn.
Vance, F. K., Duke Univ., Durham, N. C.
West, W. K., Alum. Co. of America, Alcoa, Tenn.
Wise, W. R., Captain, U. S. Army, Camp McClain, Miss.

5. Great Lakes

Abbett, R. C., Victor Div., Radio Corp. of America, Indianapolis, Ind.
Banky, J. B., Allis-Chalmers Mfg. Co., Milwaukee, Wis.
Burkhart, G. N., Jr., Duncan Elec. Mfg. Co., Lafayette, Ind.
Cooper, G. R., Purdue Univ., Lafayette, Ind.
Crouse, C. H., Allis-Chalmers Mfg. Co., Milwaukee, Wis.
Crawford, R. S., Allis-Chalmers Mfg. Co., Milwaukee, Wis.
Currin, A. G., A. O. Smith Corp., Milwaukee, Wis.
Dayton, G. R., General Elec. Co., Chicago, Ill.
Douglas, L. R., Cutler-Hammer, Inc., Milwaukee, Wis.
Drummond, B. J., General Motors Corp., Detroit, Mich.
Fisher, G. L., A-C Spark Plug Div., Gen. Motors Corp., Flint, Mich.
Fitch, W. E., Gen. Motors Corp., Anderson, Ind.
Fuchs, W. F., Allis-Chalmers Mfg. Co., West Allis, Wis.
Giraud, E. J. (Re-election), Sargent & Lundy, Chicago, Ill.
Groves, C. E., Army Air Corps, Grand Forks, N. Dak.
Hammond, R. A. (Re-election), General Elec. Co., Milwaukee, Wis.
Hendricks, H. E., Allis-Chalmers Mfg. Co., Milwaukee, Wis.
Hills, E. J., Highland Park Apprentice School, Highland Park, Mich.
Hull, S. S., Commonwealth & Southern Corp., Jackson, Mich.
Jennes, R. R., Northwestern Technological Inst., Evanston, Ill.
Johansen, H. C. (Re-election), Purdue Univ., West Lafayette, Ind.
Johnson, O. E., Guardian Elec. & Mfg. Co., Chicago, Ill.
Klutts, C. A., Buick Motor Co., Flint, Mich.
Kremmel, W. E., Cutler-Hammer, Inc., Milwaukee, Wis.
Lawton, C. D., Allis-Chalmers Mfg. Co., West Allis, Wis.
McCord, J. F., General Motors Corp., Anderson, Ind.
Miller, G. W., Allis-Chalmers Mfg. Co., Milwaukee, Wis.
Mittman, E. E., Radio Corp. of America, Indianapolis, Ind.
Morina, A. L., Allis-Chalmers Mfg. Co., Milwaukee, Wis.
Olson, R. L., Minneapolis-Honeywell Reg. Co., Minneapolis, Minn.
Poenisch, C. C., Technician, 4035 Sheridan Road, Chicago, Ill.
Potter, W. F., Potter Co., North Chicago, Ill.
Rebechini, P. G., Independent Pneumatic Tool Co., Aurora, Ill.
Reeves, J. B., Cutler-Hammer, Milwaukee, Wis.
Richardson, E. E., Public Service Co. of Ind., Indianapolis, Ind.
Seaninger, J. M., Radio & Electronic Service, Pekin, Ill.
Templin, A. T., Allis-Chalmers Mfg. Co., Milwaukee, Wis.
Thielach, H., Univ. of Mich., Ann Arbor, Mich.
Underwood, O., Minneapolis-Honeywell Reg. Co., Minneapolis, Minn.
Votaw, E., Bendix Products Corp., South Bend., Ind.
Wigington, L. M., Victor, Div., Radio Corp. of America, Indianapolis, Ind.

6. North Central

Beitman, C. R., U. S. Bureau of Reclamation, Denver, Colo.
Musgrove, E. H., D. & R. G. W. R. R., Denver, Colo.

7. South West

Anderson, R. G., Wagner Electric Corp., St. Louis, Mo.
Burwell, M. H., Kansas City Pr. & Lt. Co., Kansas City, Mo.
Crider, N. (Re-election), Union Electric Co. of Mo., Webster Groves, Mo.
Devlin, J. O., Jr., Combustion Engg. Co., Houston, Texas
Duenke, G. A. (Re-election), Moloney Electric Co., St. Louis, Mo.
Dugas, L. V., Gulf States Util. Co., Beaumont, Texas
Dyer, G. L., Southwestern Bell Tel. Co., Tulsa, Okla.
Elam, J., Univ. of Okla., Norman, Okla.
Gemoets, E. L., Tri-State Broadcasting Co., Inc., El Paso, Texas
Hope, D. L., Aircraft Accessories Corp., Kansas City, Kans.
Lassiter, J. W., Brown Shipbuilding Co., Houston, Texas
Maurer, J. J., Curtiss-Wright Corp., Robertson, Mo.
Meyer, G., Kansas City Pr. & Lt. Co., Kansas City, Mo.
Pace, C. W., Brazos River Trans. Elect. Coop., Inc., Granbury, Texas
Schelp, D. M., Wagner Electric Co., St. Louis, Mo.
Shaw, E. F., Magnolia Petroleum Co., Beaumont, Texas
Smith, C. E., Southwestern Bell Tel. Co., Tulsa, Okla.
Walker, V. R., Alum. Co. of America, Malvern, Ark.
Zahm, C. E., Southwestern Bell Tel. Co., Oklahoma City, Okla.

8. Pacific

Abramis, B. D., Consolidated Vultee Aircraft Corp., San Diego, Calif.
Bouska, J. G., Electric Storage Battery Co., Los Angeles, Calif.
Carson, R. M., Westinghouse Elec. & Mfg. Co., San Francisco, Calif.
Coleman, H. L., Douglas Aircraft Co. Inc., Los Angeles, Calif.
Dowling, R. H., Jr., U. S. Signal Office, San Francisco, Calif.
Gardner, K. N., Southern Calif. Tel. Co., Los Angeles, Calif.
Geraty, G. C., Jr. (Re-election), Joslyn & Ryan, San Francisco, Calif.
Hedges, R. E., Douglas Aircraft Corp., Santa Monica, Calif.
Jang, J., Joshua Hendy Iron Works, Sunnyvale, Calif.
Jung, B. W., Consolidated Vultee Aircraft Corp., San Diego, Calif.
Lodge, E. A., Arizona Power Corp., Camp Wood, Ariz.
Matson, M., U. S. Navy Yard, Mare Island, Calif.
Mitchell, H. H., Kelman Elec. & Mfg. Co., Los Angeles, Calif.
Moody, H. S., Los Angeles Shipbuilding & Drydock Corp., San Pedro, Calif.
Muehlhauser, H., U. S. Navy Yard, Mare Island, Calif.
Newman, L., Southern Calif. Tel. Co., Los Angeles, Calif.
Overbey, C. O., Santa Fe Ry. Co., Los Angeles, Calif.
Pattison, F. N., Jr., C. C. Moore & Co., San Francisco, Calif.
Rader, H. E., Southern Calif. Tel. Co., Los Angeles, Calif.
Schneider, J. R., General Electric Co., San Francisco, Calif.
Smallman, R. L., General Elec. Co., Los Angeles, Calif.
Sylvanus, E. C., Holmes & Narver, Los Angeles, Calif.
Taylor, J. B., Southern Calif. Tel. Co., Los Angeles, Calif.
Thorne, B. W., Jr., Public Service Dept., Burbank, Calif.
Vaitses, P. A., Walsh-Kaiser, San Francisco, Calif.
Wiley, V. G., Southern Calif. Tel. Co., Los Angeles, Calif.
Winters, F. A., U. S. Navy Yard, Mare Island, Calif.
Withers, J. W., Douglas Aircraft Co., El Segundo, Calif.
Witten, E. L., Douglas Aircraft Co., Santa Monica, Calif.

9. North West

Adams, L., Boeing Aircraft Co., Renton, Wash.
Ammerman, D. W., Aluminum Co. of America, Spokane, Wash.
Burton, J. H., Pan-American Airways, Seattle, Wash.
Cook, D. W., Pan-American Airways System, Seattle, Wash.
Dau, R., Pan-American Airways, Seattle, Wash.
Downing, K. O., Pan-America Airways, Seattle, Wash.
Hartsock, P. L., Alum. Co. of America, Vancouver, Wash.
Jaccard, G. W., Jr., Boeing Aircraft Co., Seattle, Wash.
Kampschor, D. E., Westinghouse Elec. & Mfg. Co., Salt Lake City, Utah.
Monroe, J. D., Boeing Aircraft Co., Renton, Wash.
Nelthorpe, F. A., Jr., Puget Sound Pr. & Lt. Co., Seattle, Wash.
Ralstin, R. E., Westinghouse Elect. & Mfg. Co., Spokane, Wash.
Roberson, L. N., Dept. of Public Works, Seattle, Wash.
Samson, R. S., Puget Sound Pwr. & Lt. Co., Bremerton, Wash.
Stein, J. J., Puget Sound Navy Yard, Bremerton, Wash.
Swanson, J. O., Bonneville Power Adm., Vancouver, Wash.
Wittkopf, J. J., Oreg. State Col., Corvallis, Oreg.

10. Canada

Fong, W. H., Montreal Light Heat & Power Co., Montreal, Que., Can.
Hayles, O. J., Northern Elec. Co., Montreal, Que., Can.
Humeniuk, P., Univ. of Toronto, Swansea, Ont., Can.
Lahti, M. E., National Res. Council, Ottawa, Ont., Can.
Marchant, C., Radio Valve Co. of Canada, Ltd., Toronto, Ont., Can.
McCowan, W., Can. Gen. Elec. Co., Scarboro, Ont., Can.
McKeagan, E. A., Can. Gen. Elec. Co., Montreal, Que., Can.
Price, E. G., Northern Electric Co., Montreal, Que., Can.
Taylor, W. M., Royal Canadian Navy, Halifax, N. S., Can.
Vogan, B., Polymer Corp., Sarnia, Ont., Can.
Wagner, R. N., Aluminum Co. of America, Spokane, Wash.
Wood, J. R., Canadian Gen. Elec. Co., Peterboro, Ont., Can.

Elsewhere

Aldana, H. L., Comision Nacional Irrigacion, Mexico, D. F., Mex.
Campistrous, V. H., Rio Negro Hydroelectric Dev., Montevido, Urug., S. A.
Cuenca, L. M., Street Lighting Dept., Mexico, D. F., Mex.
Declemente, G. E., National Powder Factory, Santa Fe, D. F., Mex.
de la Torre R. M., Westinghouse Elec. Internacional, Mexico, D. F., Mex.
Diaz, M. M. de O., Distribuidora Electrica, Mexico, D. F., Mex.
Dultzin, S., General Supply Co., Mexico, D. F., Mex.
Eberstadt, S. R., Industrial Hygiene Dept., Mexico, D. F., Mex.
Flores, S. B., Cia SKF Golfo Y Caribe, S. A., Mexico, D. F., Mex.
Fortoul, G., Mexican Lt. & Pr. Co. Ltd., Mexico, D. F., Mex.
Gomez, V. I., Mexican Lt. & Pr. Co., Mexico, D. F., Mex.
Graf, G. J., Electrical Contractor, Lomas de Chapultepec, Mexico, D. F., Mex.
Heddrich, G., LaCasa Electrica de Guadalajara, S. A. Guadalajara, Jal, Mex.
Marteny, M. L., Lago Oil & Transport Co. Ltd., Aruba, N. W. I.
Nieto, A., Nieto & Cia., Celaya, Gto. Mex.
Olavarrieta, F. T., Cia Distribuidora Westinghouse, Mexico, D. F., Mex.
Orozco M. J., National Public Utilities Comm., Mexico, D. F., Mex.
Rodriguez G. L., National Commission of Irrigation, Mexico, D. F., Mex.
Rojas, H. C., Mexican Lt. & Pr. Co., Mexico, D. F., Mex.
Rubio, J. M., Cia Distribuidora Westinghouse, S. A. Mexico, D. F., Mex.
San Vicente, G., Sociedad Electromecanica, Mexico, D. F., Mex.
Vazquez-Praderi, F., Rio-Negro Hydroelec. Dev., Montevideo, Urug., S. A.

Total to grade of Associate

United States and Canada 411

Elsewhere 22

OF CURRENT INTEREST

Underwriters' Laboratories, Inc., Reviews History of Its Development in 50 Years

Underwriters' Laboratories, Inc., nonprofit organization established in 1894 by the National Board of Fire Underwriters as the official testing station of the capital-stock fire-insurance business, celebrated in February the anniversary of its first 50 years of public service. From its modest beginning above a fire-patrol station in Chicago, Ill., as a one-engineer one-room office with only $350 worth of electrical equipment, it has developed into a national concern with four testing stations in major industrial sections of the United States. Today its central station in Chicago comprises approximately 130,000 square feet of floor area, and is said to be one of the best examples of fire-resistive construction in this country.

Underwriters' Laboratories, Inc., was an outgrowth of the first Chicago World's Fair, the Columbian Exposition of 1893. A feature of the Fair was to be a lavish display of incandescent-lamp lighting in and on the buildings. During construction of the fair-ground buildings a number of fires occurred, some of which were caused by the new system of lighting. Apprehensive that the new method might prove hazardous, insurance interests in Boston sent an engineer, William Henry Merrill, later the founder-president of the Laboratories, to investigate the situation.

Riding behind the horses at each call to the fairgrounds, Merrill had to determine what piece of electrical equipment, if any, had caused the fire, and why. Report number 1, covering the investigation of an electrical insulating material, was dated March 24, 1894. Since that date the Laboratories has pursued a long and close association with the electrical industry.

Merrill soon consolidated his equipment with that of William C. Robinson, chief engineer and vice-president of the new organization, who had been sent by insurance underwriters to investigate automatic sprinklers in the Chicago area. As industrial expansion began to gain momentum in the United States, the new enterprise became closely associated with it, rapidly adding to the scope of its activities until it attained its present multipurpose coverage.

In the meantime, similar investigations on behalf of insurance interests, oftentimes attaining different results, were conducted in other cities. To avoid confusion and to unify the tests, the NBFU, in 1894, gave official recognition to the Chicago testing station, and Underwriters' Laboratories, Inc., was born. Having outgrown its original and supplementary locations, the new corporation then moved into its first complete building, and in 1904 it occupied the first of the series of buildings constructed on its present site to house expanding facilities.

Fire, the original consideration, is still the principal one at the Laboratories today. The prevention of accidents, electric shocks, explosions, burglaries, and related dangers, however, also is included in the scope of activities. Seventeen departmental laboratories equipped with much unusual and unique, as well as the standard, test equipment are represented at the main testing station in Chicago.

Because of the increasing volume of testing required by eastern manufacturers, a testing station was opened in New York, N. Y., in 1912. Work at this station is primarily in electrical, fire-alarm, and burglary-prevention fields. To serve the western part of the United States a third station, mainly for electrical work, was opened in San Francisco, Calif., in 1923. For extra hazardous work involving high explosives, toxic gases, and other dangerous products, a fourth testing station was established in the country about 35 miles out from Chicago.

"Know by Test," an admonition of its founders, is the principle underlying the Underwriters' Laboratories' activities. It was recognized early that visual inspection of the constructional features of a product and small-scale tests were not adequate to determine whether a device would operate satisfactorily or might create a hazard during normal or abnormal operation. Consequently, large-scale tests on full-size commercial products are the rule. Furnaces for large wall sections containing full-scale fire doors or fire windows, and three-phase electric loads to match and exceed the ratings of most commercial switches are among the sizable apparatus which is standard equipment at the testing stations.

In addition to their tests, Underwriters' Laboratories has compiled about 175 published Standards, with additional tentative requirements, defining what performance and what construction is needed for safe service. Each of these Standards covers a class of products and serves as a guide both for the manufacturers and for the corporation engineers who conduct investigations.

One of the outstanding functions of the Laboratories is its inspection service. All of the products that have passed the test investigations at one of the stations are inspected periodically at the factories. A corps of technically trained men operating from 185 centers of production in the United States and Canada, in London, England, and Honolulu and Hilo, Hawaii, have made in recent years, more than 85,000 annual factory visits. These investigations involve examination of the raw materials of which the article is made, inspection of partially completed products on the production line, and tests of representative samples of the finished product selected at random.

"Underwriters' Laboratories, Inc. Inspected" labels, serially numbered, are issued by inspectors for use on products passing this factory investigation. To date 375,000 products, widely diversified, have

Figure 1. View of the electrical laboratory, Underwriters' Laboratories, Inc., in the early days. Sash weight and water-barrel variable resistor in the foreground were part of the original $350 worth of equipment

Figure 2. A corner of the present electrical laboratory, Underwriters' Laboratories, Inc., at the main testing station in Chicago, Ill. The photograph was made at the instant of explosion of a switch during an overload test

been approved and are listed in the corporation's booklets of tested and inspected items. Four such booklets are issued annually, covering fire-protection equipment; gas, oil, and miscellaneous equipment; electrical equipment; and accident-hazard, automotive, and burglary-protection equipment. Supplements to the first two lists are issued semi-annually, and the electrical list is brought up to date each month. In 1943, 200,000 copies were distributed free of charge to federal, state, and city authorities, industry, the armed services, inspectors, insurance people, and purchasing agents.

War and Postwar Adjustment Policies Recommended in Baruch–Hancock Report

"Victory is our first and only duty, but just as we prepare for war in time of peace, so we should prepare for peace in time of war," stated Bernard M. Baruch and John M. Hancock in transmitting their recent "Report on War and Post-War Adjustment Policies" to Director James F. Byrnes of the Office of War Mobilization. Messrs. Baruch and Hancock comprise the advisory unit for war and postwar adjustment policies of the Office of War Mobilization. In addition to the letter of transmittal and the report proper, the report booklet includes addenda giving a more extensive treatment of three subjects: contract termination, surplus property, and tightening the industrial war machine.

Declaring that "there is no need for a post-war depression, the letter of transmittal further states: "In the reconversion and readjustment will come improvements in our standards of life—better houses, better clothes better food, better safeguards for children, better health protection, and wider educational opportunities. These bring hope for the future instead of fear; they give security instead of unrest."

The specific assignment of the advisory unit was to study the immediate demobilization policies which have to do with the stimulation of war effort, since victory is the first essential, and with the preparation for peace to follow victory. Messrs. Baruch and Hancock summarize their major suggestions as follows:

"1. Getting us all back to work in peacetime enterprises. This may require a special authority under the director of war mobilization to give its entire attention to the problem of bringing jobs to all workers, with emphasis laid upon the returning service men and service women who are our first concern.

"2 Taking the Government out of business by:

(a). Payments for work done and work under way. In connection with this phase of the problem, we have assembled a complete 'financial kit' that should prove effective. The Government must pay its debts, and pay them quickly and fully, so that business will have its working capital freed for pay rolls and purchase of materials.

(b). These payments can be made with ample protection to the Government against fraud.

(c). Move out and store war materials from plants so as to make room for equipment and materials for civilian production.

(d). Centralize the control and disposal of surpluses of all types in such a way as to bring them into ready and effective use and insure orderly markets. This, too, may require a special administrator in the Office of War Mobilization.

"3. A general tightening up of the industrial war front so as to finish the bloody business with finality, and thus be ready for peace.

"4. Spreading acceptance by war contractors of the 'Uniform Contract Article,' as recommended by us and approved by you [Director Byrnes].

"5. Place all war agencies under running review to cut them down as their work dwindles; also review of all war industrial controls.

"6. Immediate extension of laws governing price control, priorities and requisitioning, all three expiring this year.

"7. Early engineering on public works to be ready if needed to fill in the valley of unemployment.

"8. Provide credit means for those requiring it during the adjustment period, particularly for the smaller business groups and returning servicemen.

"9. Prepare now for future action reducing taxes from war to peacetime levels, thereby providing necessary incentive for initiative and enterprise and stimulating employment.

"10. Prepare an emergency 'X day' reconversion plan to be used in the event of a sudden collapse of Germany so as to enable us to go on with our crusade against Japan and at the same time to prevent the dislocation resulting from lack of preparation. This phase of the broader plan is to be worked out by the armed services with the War Production Board."

Discussing the hazards of pressure groups to our postwar economy, the report deplored the widespread "loose parroting" of the slogan: "If individual enterprise fails to provide jobs for everyone, it must be replaced by some one of the other systems that are around." Pointing out that the war has been a crucible for all sorts of economic systems, the report declares that: "the American system has outproduced the world. America's productive capacity can perform still another miracle in a fine and lasting peace. It will not do so if pressure groups are permitted to turn that productive capacity into a battleground for their own selfish interests or inflate ourselves out of the world market."

Expressing their belief that a general tightening of the war machinery is necessary—both for mobilization and demobilization—Messrs. Baruch and Hancock state that "the changing conditions of the war in this respect can be pictured as dislocations that loosen the war mobilization machine and there must be a steady tightening up." Their recommendations for a general tightening of the entire Government war machine are summarized as follows:

"1. A running view of the functions of all war agencies by the Bureau of the Budget, reporting regularly to the director of war mobilization with recommendations for cutting down the agencies as their work dwindles.

"2. Intensification of the fine work already being done in sweating out unnecessary requirements in the services' programs.

"3. An early, equally effective review of the programs for raw-material production, stockpiling, imports, subsidies, and premiums to marginal producers so as not to continue any of these programs beyond being needed.

"4. Early review of all wartime materials controls and limitation measures to determine under what conditions these orders can or should be modified.

"5. Strengthening of the industry advisory committees in the War Production Board.

"6. Tightened handling and advance planning of new contracts and contract cancellation.

"7. Closer working together of the WPB and the OPA to avoid pricing delays in the resumption of civilian production.

"8. The armed services to furnish all civilian agencies full information in adequate time for these agencies to do their planning.

"9. The civilian agencies to organize themselves to use this information effectively.

"10. A running conspectus by the Office of War Mobilization of the tasks assigned each agency.

"11. No new demobilization agency needed at this time."

The report concludes with a section devoted to the "Uniform Termination Article" previously recommended by the advisory unit for war and postwar adjustment policies,

which was made effective by a directive to all procurement agencies issued by Director of War Mobilization James F. Byrnes in January. Briefly, the termination article provides that the government may terminate a prime contract at any time by giving notice. A major portion of the article consists of a statement of principles on cost determination. This cost statement is based upon the recognition only of those costs that are properly allocable to the contract and only to the extent that they are quantitatively reasonable for the performance of the whole contract.

INDUSTRY . . . . .

Bell System Reports Extended and Improved Service in 1943

Increased radiotelephone service overseas, expansion of transcontinental telephone facilities, and limited installations of new developments offering improved quality and speed of service are some of the means by which the American Telephone and Telegraph Company has met hitherto unprecedented wartime demands, according to its annual report for 1943.

Overseas telephone service was extended during 1943 to the Union of Soviet Socialist Republics by means of a radiotelephone circuit established between New York and Moscow. Service also was inaugurated between the United States and Curacao, in the Netherlands West Indies, over a New York–Willemstad circuit, and additional facilities have been provided to Brazil, Venezuela, Central America, and Hawaii.

Since the start of the national-defense program in 1940, the number of Bell System telephones in service has increased more than 4,500,000, the daily number of conversations handled by the System has increased more than 12,000,000, and the number of long-distance conversations has increased 2½ times. Despite the unusual difficulties, thousands of additional public telephones have been provided in and near military establishments, with more than 400 special telephone centers staffed by operators especially trained to handle the calls for men and women in the armed services. In a few instances telephone busses or trailers housing booths and attendants have been used, pending installation of permanent facilities.

Growth of automatic or dial switching has been one of the outstanding changes in telephone service since World War I. A significant step in this growth as it affects long-distance calls was taken in 1943 when a new toll switching office at which the operator dials directly the number in the distant town or city desired by the subscriber, was installed for operation in Philadelphia. Another such development, known as "automatic ticketing," ultimately will enable subscribers in metropolitan areas to dial directly a substantial part of their calls to nearby points which now must be placed through an operator. Distinctive feature of the equipment is the automatic preparation for each call of a printed ticket showing all the information needed for charging the call to the subscriber. A form of this development has been put into commercial use in a suburban office in the Los Angeles area. A detailed reference to this development is made in the technical paper, "Automatic Ticketing of Telephone Calls," by O. A. Friend (*AIEE Trans., March '44, pp 81–8*).

Bell Telephone Laboratories, Inc., the Bell System's research organization, has engaged in over a thousand war development projects, more than half of which have been completed and many of which have found effective practical application in actual combat. These projects include all kinds of electrical communication, both wire and radio, used over land or sea and through air and water. They are not limited to communications, however; many of them involve applications of electronics to other problems of warfare.

The Western Electric Company, Inc., manufacturing branch of the System, is now engaged almost exclusively in the manufacture of materials of electronic and other war communication equipment. One of the many new war products is an electrically operated gun director, representing an entirely new principle in fire control.

Sales to the United States Government amounted to $596,112,000 in 1943, representing 83 per cent of the total. Telephone facilities along the Alaskan military highway, and similar facilities for a line across Newfoundland, are examples of equipment the company was called upon by the Government to manufacture and install.

A number of new developments in the laboratories, either deferred by the war or resulting from war research, will be explored as soon as possible. One, of course, includes the rapid extension of coaxial cable systems, which has been postponed because of the war. These cables, which are capable of carrying several hundred telephone conversations simultaneously in two metal tubes a little larger than a lead pencil, with a copper wire in each extending along its axis, are of particular interest in connection with postwar television developments.

Leo H. Baekeland, Inventor of Bakelite Dies. Leo H. Backeland, scientist and inventor of international repute died at Beacon, N. Y., February 23, 1944. Doctor Backeland, who was born in Ghent, Belgium, in 1863, received the degrees of bachelor of science in 1882 and doctor of science, maxima cum laude, in 1884 from the University of Ghent. After a short time on the faculty of that university, he came to the United States on a traveling scholarship in 1889. Founding the Nepera Chemical Company in 1893 for the manufacture of photographic papers, he soon invented the printing paper known as Velox which he sold to the Eastman Kodak Company in 1899. Doctor Backeland then established in Yonkers, N. Y., the research laboratory in which he evolved the synthetic product which he named bakelite and which became the basis of the plastic industry. In 1910 he formed the Bakelite Corporation and served as its president until his retirement in 1939. He also was associated with C. P. Townsend and E. A. Sperry in the development of the Townsend electrolytic cell. He had served on the advisory committee on chemistry of the Department of Commerce

Bell System Statistics

	Dec. 31, 1925	Dec. 31, 1930	Dec. 31, 1935	Dec. 31, 1940	Dec. 31, 1943	Increase During 1943*
Number of telephones (a)	11,909,578	15,187,296	13,573,025	17,483,981	21,246,629	1,233,697
Number of central offices	6,147	6,639	6,896	7,052	7,311	107
Miles of pole lines	394,529	428,212	407,454	399,838	412,281	749
Miles of wire:						
In underground cable	27,769,000	45,116,000	47,639,000	54,339,000	59,321,000	293,000
In aerial cable	12,835,000	23,777,000	26,425,000	30,307,000	33,111,000	23,000
Open wire	4,339,000	5,231,000	4,562,000	4,660,000	4,938,000	13,000
Total	44,943,000	74,124,000	78,626,000	89,306,000	97,370,000	257,000
Average daily telephone conversations** (b)	50,141,000	64,034,000	60,290,000	79,303,000	86,107,000	786,000
Total plant	$ 2,566,809,000	$4,028,836,000	$4,187,790,000	$4,747,674,000	$5,387,790,000	$91,132,000
Operating revenues**	$ 737,560,000	$1,075,228,000	$ 919,116,000	$1,174,322,000	$1,648,077,000	$178,814,000
Taxes**	$ 58,113,000	$ 84,732,000	$ 94,507,000	$ 184,770,000	$ 372,936,000	$ 52,383,000
Number of employees (c)	292,902	318,119	241,169	275,317	342,980	15,873
Number of American Telephone and Telegraph Company stockholders	362,179	567,594	657,465	630,902	651,711	8,690

* Decreases shown in italics. ** For year ending December 31.

(a) Excludes private-line telephones numbering 100,313 on December 31, 1943, but includes telephones of about 6,200 connecting companies and more than 60,000 directly and indirectly connecting rural or farmer lines and systems. The total number of telephones in the United States which can be interconnected is approximately 26,315,000.

(b) For the year 1943 there were approximately 82,195,000 average daily local conversations and 3,912,000 toll and long-distance conversations, a decrease of 1.5 per cent and an increase of 14.2 per cent, respectively, over the year 1942.

(c) In addition, the Western Electric Company and the Bell Telephone Laboratories had 96,266 employees on December 31, 1943.

since 1925, on the United States Naval Consulting Board since 1915 and on the National Research Council. Doctor Baekeland was a member or honorary member of many French, Belgian, and British as well as American scientific societies. He had been honored with numerous medals and awards for his achievements.

Instant-Starting 40-Watt Fluorescent Lamp Now Available

Development of an instant-starting 40-watt white Mazda fluorescent lamp has been announced by General Electric Company lamp department at Nela Park, Cleveland, Ohio. It has the same rated life when operated with instant-starting ballasts as that of the present 40-watt fluorescent lamp which is started by means of the conventional switch, and by preheating.

Limited quantities of the instant-starting lamp will be made available for shipment on and after May 1 for war-production installations equipped with instant-starting ballasts, it is said.

Zenith Radionics Corporation Formed. Formation of the Zenith Radionics Corporation of New York as a subsidiary of the Zenith Radio Corporation recently was announced by J. J. Nance, vice-president and director of sales for the parent company. Establishment of the new corporation, which will be the distributor of Zenith radionics products in the area formerly covered by Colen and Gruen, New York, and E. B. Latham, New Jersey, marks a departure from the parent company's policy of independently franchised distributorships. However the parent company will adhere to its former policy except in the highly concentrated areas of New York and Chicago. H. J. Wines, formerly general sales manager of the New York and Chicago branches of the Frigidaire division of the General Motors Corporation, has been named general manager and a director of the New York corporation. E. F. McDonald, Jr., president of the Zenith Radio Corporation also heads the new corporation.

16 Groups Inaugurate National Postwar Conference

A declaration of their recognition of joint responsibility for establishing an economy of plenty and preventing mass unemployment, ruinous farm prices, and violent business cycles, came from the delegates of 16 groups representing many facets of our national economy, capital, labor, farmers, the railroads, war veterans, and fraternal organizations, meeting recently in Atlantic City, N. J., in the first session of a permanent National Postwar Conference.

Basing their belief in the need for the new organization on the theory that an effective democratic economy must be propelled by the voluntary joint action of its component groups as part of their responsibility to society, the conferees outlined the postwar objectives for which they would work as "—an economy of plenty instead of scarcity—an opportunity for people to have jobs and increasingly better living standards and educational advantages—an opportunity for people to save and invest." The conference emphasized the fact that if the groups concerned did not "do these things together then the task will fall upon the government."

The delegates unanimously concluded "that the highest degree of prosperity and employment is assured when widespread buying power of the public, based on the production of goods and services, is maintained. It is further agreed that over any long period of time no one group can be prosperous unless the other groups are also prosperous."

Each of the organizations represented was requested to designate one member and one alternate to an organization committee to arrange, for future conferences at about two-month intervals. Invitation to groups other than the original 16 also are contemplated. The future conferences will consider: agricultural problems; capital and credit; currency stabilization; distribution of products; financing social security; foreign trade; reconversion, including the problems of contract termination, renegotiation, disposition of government-owned plants, equipment and supplies, and surplus agricultural products; and taxation.

The organizations represented at the first conference were: the Aeronautical Chamber of Commerce of America, the American Bankers Association, the American Farm Bureau Federation, the American Federation of Labor, the American Legion, the Association of American Railroads, the Chamber of Commerce of the United States, the Committee for Economic Development, the Congress of Industrial Organizations, the Investment Bankers Association of America, the Kiwanis International, the National Association of Manufacturers, the National Foreign Trade Council, the National Council of Farm Cooperatives, the National Grange, and the Rotary International.

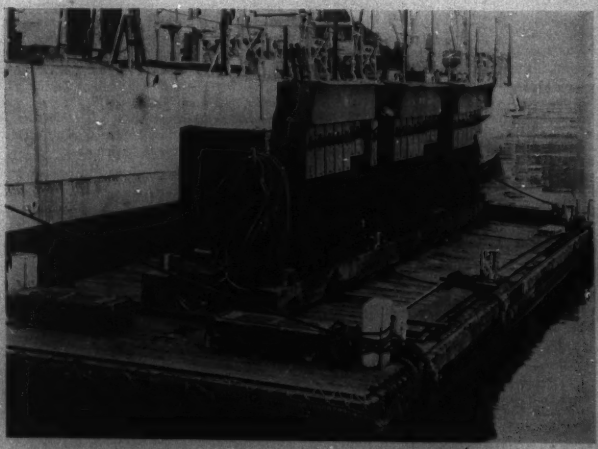
WAR PROGRAM • •

Critical Materials Still Short

The possible availability of critical materials for the manufacture of civilian goods has been a subject of much discussion recently. A recent report of the War Production Board offers a few facts for consideration.

The most critical materials used in the electrical industry have been growing scarce as the war has progressed. Barring any radical changes in the requirements of the armed forces, there seem to be adequate supplies of aluminum for essential uses. Copper and steel are fairly well balanced between supply and demand. Nickel, which is used mainly in ferroalloys, is extremely

Barges Carry Testing Equipment to New Ships



These barge-mounted immersion-type load resistors shown in the fitting-out basin of the Seattle–Tacoma Shipbuilding Corporation, Seattle, Wash., are connected by cable to the switchboard of newly launched ships to test auxiliary generating equipment. The resistors consist of banks of General Electric heaters mounted in water tanks in which the generating-equipment energy is absorbed and dissipated. Two of the barge's three tanks are for 440-volt 3-phase wye and delta connections, each connection being for 348 kw in about 6-kw steps by manual switching. The third tank is for 120 volts, single phase, and totals 9.35 kw in about 1.5-kw steps

Future Meetings of Other Societies

American Society for Testing Materials. 47th annual meeting, June 26–30, 1944, New York, N. Y.

American Society of Refrigerating Engineers. 31st spring meeting, June 5–7, 1944, Pittsburgh, Pa.

American Society of Mechanical Engineers. Semi-annual meeting, June 19–20, 1944, Pittsburgh, Pa.

Canadian Electrical Association. Annual meeting, June 22–23, 1944, Murray Bay, Que.

Edison Electric Institute. Annual conference, June 6–7, 1944, New York, N. Y.

Electrochemical Society. Spring meeting, April 12–15, 1944, Milwaukee, Wis.

Illuminating Engineering Society. Southwestern regional meeting, April 25, 1944, Dallas, Tex.; Great Lakes regional meeting, May 20, 1944, Cincinnati, Ohio.

Midwest Power Conference. April 13–14, 1944, Chicago, Ill.

National Electrical Manufacturers' Association. April 23–7, 1944, Chicago, Ill.

National Fire Protection Association. May 8–11, 1944, Philadelphia, Pa.

Pacific Coast Electrical Association. Northern section, May 10, 1944, San Francisco, Calif.; southern section, May 17, 1944, Los Angeles, Calif.

Radio Manufacturers Association. 20th annual convention, June 6–7, 1944, Chicago, Ill.

Society of Motion Picture Engineers. 55th semi-annual conference, April 17–19, 1944, New York, N. Y.

short in supply at the present, and conditions are not expected to improve, although the supply has been increased slightly in the past year.

Tin and rubber both are extremely scarce, since the war in the Pacific has blocked imports from that area. We still receive small quantities of new tin from Bolivia, but the political status there makes shipments questionable. In the meantime, we have stretched our supply by substitutions, downgrading, electrolytic plating, and salvage. We are replacing our rubber stock almost entirely with synthetic material. Zinc has been scarce for the last two years, but slab zinc is being released in freer quantities than previously. Paper and wood are both becoming less abundant, the latter having been used in many instances as a substitution for metals, but now it is just as much in demand as metallic substances.

Underwater Telephone Line Made From Spiral 4 Cable

The first underwater telephone line ever constructed from spiral 4 cable was laid in the South Pacific area from Signal Corps headquarters on Renidova Island to two divisions on the mainland under the leadership of Major George A. Reeves in July 1943, according to reports from Colonel Francis L. Ankenbrandt. Fighting was desperate in that section of the South Pacific Theater of Operations, and it was inadvisable to await the arrival of submarine telephone wire. This spiral 4 cable is often used by the Signal Corps to construct semi-permanent wire channels to the front lines, but it was not intended to withstand the pressure required for this application. To assure maximum waterproofing, it was necessary to seal the connectors of the cable with rubber and friction tapes, as they were the only materials available. Extreme care had to be enforced in laying the cable, so as not to bruise nor sever it by the sharp coral. Anchors were made from barbed wire stakes and laid at intervals of about one eighth of a mile.

A crew of 50 men was successful in laying this cable a distance of approximately nine miles through hazardous jungles, muddy plantations, and part of the Pacific Ocean which was 1,700 feet deep at the point crossed. The party encountered heavy fire from Japanese artillery and aircraft during its progress. Two submarine circuits were linked together at Roviana Island, in the middle of the channel of water, with field wire. Time has been the deciding factor in determining the success of this experiment, and it has been proved that ordinary tape-bound spiral 4 cable, if necessary, can meet the conditions that usually necessitate a waterproof cable.

OTHER SOCIETIES

ASA Issues Five New and Revised War Standards

Three new war standards applicable to the field of radio and two revised editions of the war standards for electric panel-type instruments and shunts have been issued recently by the American Standards Association.

The American War Standard Fixed Ceramic Dielectric Capacitors, (Temperature-Compensating Types) *C*75.12, available for 35 cents a copy, and the American War Standard Crystal Unit CR-1/AR, *C*75.11, 25 cents a copy, were prepared with the co-operation of representatives of industry and the Armed Forces at the request of the War Production Board. The American War Standard Porcelain Radio Insulators *C*75.14, 50 cents a copy, is the fourth and last standard in the series prepared by the IRE committee on insulation-material specifications for the military services.

The American War Standard Electrical Indicating Instruments ($2^1/_2$- and $3^1/_2$-Inch, Round, Flush-Mounting, Panel-Type) *C*39.2, 50 cents a copy, was revised after a year's experimental use by the electrical industry and the Armed Forces, and the American War Standard External Ammeter Shunts for Panel-Type Instruments *C*39.5, 25 cents a copy, was revised to simplify the ranges of external ammeter shunts which are used to extend the measurement range of electric instruments.

Copies of all these standards can be obtained at the prices quoted, from the ASA, 29 West 39th St., New York 18, N. Y.

ASTM Develops Bibliography on Electrical Contacts

The American Society for Testing Materials through its committee *B*-4 on electrical-heating, electrical-resistance, and electric-furnace alloys has developed and published, "Bibliography on Electrical Contacts." This extensive compilation of references to the literature on electrical contacts should prove a valuable aid to those engaged in conducting tests for evaluating different materials and types of contacts. The information provided will enable comparisons of different materials and methods of operation to be made. The abstracts included were taken chiefly from *Service Abstracts* and *Chemical Abstracts* although numerous other sources also were utilized. Because of the wide variety of problems involved in the successful functioning of contacts—microphysics of the electric arc, metallurgy of the contact materials, mechanics of the operating mechanisms, and so forth—references which have reasonable connection with those problems are included. The abstracts are listed in chronological order and for convenience there is a detailed subject and author index. The book contains 150 pages with heavy board covers, size 6 by 9 inches. Copies may be obtained at five dollars each from the ASTM, 206 South Broad Street, Philadelphia 2, Pa.

Iron and Steel Engineers Establish New Award

A new award has been established by the Association of Iron and Steel Engineers in commemoration of the late John F. Kelly, former managing director of the Association. This award, consisting of a certificate reciting its origin and the specific accomplishment for which it is granted, will be presented annually to that author whose paper, published by the Association, has been concluded to be of greatest value in the advancement of engineering or operating practices in the iron and steel industry. Entries for the award will be the papers published during each calendar year, although some may have been presented at meetings the previous year. Papers contributed voluntarily and not presented at meetings also will be eligible in the judging. Although it is not necessary that the author be a member of the AISE, he must be connected directly with the iron- and steel-producing industry. The award will be made by the board of directors of the Association on the recommendation of its executive committee at the annual fall meeting following the close of the calendar year.

HONORS

Doherty Receives Host of Honors

Robert E. Doherty (F '39) president of Carnegie Institute of Technology, Pittsburgh, Pa., was recently named Pittsburgh's "Man of the Year" by the city's Junior Chamber of Commerce, in recognition of his outstanding contributions to civic affairs. The selection, announced at the chamber's annual banquet, was only one of the many diverse honors conferred lately upon the engineering educator.

Early in February, as a tribute to his achievements and status in the fields of engineering and technical education, Doctor Doherty was made an honorary member of the Engineering Institute of Canada. A few days later he was appointed by President Roosevelt a member of the board of visitors to the

"Self Portrait" by Robert E. Doherty (F'39) awarded first prize for oil paintings at the 34th annual exhibition of the Associated Artists of Pittsburgh. It was on display at the Carnegie Institute Galleries, Pittsburgh, Pa., from February 17 to March 16, 1944

United States Naval Academy, Annapolis, Md.

Next came the announcement that a street in Schenectady, N. Y., had been named for him. It is one of four streets leading to a new municipal housing project, known as Steinmetz homes, in honor of Charles P. Steinmetz, late famed scientist of General Electric Company. Doctor Doherty was associated with Doctor Steinmetz for many years.

Recognition of his versatility in another field—this time, the arts—came with the award of first prize in the 34th exhibition of the Associated Artists of Pittsburgh for his "Self Portrait" oil painting. Painting has been his chief hobby for a number of years, but this is the first outstanding recognition he has received in this field.

Doctor Doherty has long been active in the affairs of the AIEE. In 1937 he received the AIEE Lamme Medal award "for his extension of the theory of a-c machinery, his skill in introducing that theory into practice, and his encouragement of young men to aspire to excellence in this field." He was chairman of the education committee from 1931 to 1933, and has served on the committees on electrophysics (now basic sciences), power transmission and distribution, and the technical program committee. Currently he is serving on the Edison Medal committee.

Faraday Medal Awarded to Langmuir. The Faraday Medal of the Institution of Electrical Engineers, London, England, has been awarded to Irving Langmuir, associate director of the research laboratory of the General Electric Company, Schenectady, N. Y. Doctor Langmuir is the fourth American to receive the medal which was established in 1922 and is bestowed for world-wide services to electric science. The other American recipients of the medal were: Elihu Thomson, F. B. Jewett (F'12), and W. D. Coolidge (M'34). Doctor Langmuir, who was honored with the Nobel Prize in chemistry in 1932, has been associated with the development of modern high-vacuum tubes, and the mercury condensation pump and has engaged in studies of tungsten and thoriated tungsten filaments, the gas-filled incandescent tungsten lamp, the atomic hydrogen welding process, and oil films.

EDUCATION • • •

New Organization Formed to Assist Technical Schools

A proposed Code of Minimum Standards for Approved Technical Schools has been set up by the National Council of Technical Schools, a new organization formed in January 1944 to occupy that area of the educational field between the usual trade chool and the professional engineering chool.

The development of sound educational standards and ethical business practices in the technical and semiprofessional fields is one of the main objectives of the Council. Its constitution also stipulates that it be active in the engagement of research in the advancement of educational methods, the cooperation with agencies in the promotion of adult education, and the maintenance of high standards and sound policies in educational relations with the public.

The Code of Minimum Standards contains a tentative outline of the educational, administrative, and ethical requirements member schools must possess. Requests for this pamphlet and constructive suggestions or criticisms should be sent to J. S. Noffsinger, director, The National Council of Technical Schools, 839 17th Street, Washington 6, D. C.

JOINT ACTIVITIES

Engineering Foundation Report. The Engineering Foundation, joint organization of the Founder Societies, has announced the availability in booklet form of its 1942–43 annual report. A brief summary of this report appeared in *Electrical Engineering*, January 1944 (pages 37–8). In full, it contains a financial statement; report on activities of member societies; officers, members, and committees; list of contributors; and publications. Copies may be obtained by addressing The Engineering Foundation, 29 West 39th Street, New York 18, N. Y.

LETTERS TO THE EDITOR

INSTITUTE members and subscribers are invited to contribute to these columns expressions of opinion dealing with published articles, technical papers, or other subjects of general professional interest. While endeavoring to publish as many letters as possible, Electrical Engineering reserves the right to publish them in whole or in part or to reject them entirely. Statements in letters are expressly understood to be made by the writers. Publication here in no wise constitutes endorsement or recognition by the AIEE. All letters submitted for publication should be typewritten, double-spaced, not carbon copies. Any illustrations should be submitted in duplicate, one copy an inked drawing without lettering, the other lettered. Captions should be supplied for all illustrations.

Mathematical Training for Young Engineers

To the Editor:

The opinions of men from industry on how much and what kind of mathematics are to be included in the undergraduate study of engineering are always of great interest to teachers of engineering, but it is quite perplexing when C. A. Powel (*EE, Feb. '44*) writes: "There should be an elective in differential equations for those students who are mathematically inclined," apparently assuming that differential equations may be of use only in postgraduate work. Whereas A. R. Stevenson, Jr., in the *Journal of Engineering Education*, May 1943, writes: "A good many undergraduate college courses include differential and integral calculus, but do not include any differential equations. Calculus is not usable on any but the most simple engineering problems unless one knows differential equations." Who is right?

The division which Mr. Powel makes as to the three levels of mathematical technology are quite interesting. In this connection it would be of interest to know how many recent graduates who had only as much mathematics as prescribed by Mr. Powel for undergraduates are capable of reading the series of articles published last year (March to September 1943) in *Electrical Engineering* on "Ultrashort Electromagnetic Waves," or for that matter most of the articles which appear in the *Proceedings* of the Institute of Radio Engineers. And finally did Mr. Powel take into consideration the mathematical needs of students in communications when he relegated the study of Maxwell's equations to the candidates for a Doctor's degree?

J. A. STRELZOFF (A'43)
(Assistant professor of electrical engineering, Michigan State College, East Lansing)

Symbol Standardization Needed

To the Editor:

May I express my appreciation for the Number 3 AIEE *Bulletin* for the armed services just recently received.

I am now stationed at the Signal Corps Standards Agency, Red Bank, N. J. This work is much more definitely in line with engineering activities. It consists in boiling

down the number of types of components which have expanded like mushrooms in the tremendously active field of radio. In addition to reducing the number of types, we are, of course, taking every step to increase the quality and it does seem that the whole program is beginning to work out. It is the co-operation of the engineers in the electrical industry that has enabled us to accomplish what we have in this direction. In particular, vacuum tubes, meters, ceramics, capacitors, and resistors are now well in hand, and a recent meeting emphasized the need for bringing together the conflicting symbols which have plagued communications and power for years. It seems that all of this well may promote the war effort by giving better and greater quantity production with the same staff and facilities in these essential lines.

R. H. RANGER (M '22)

(Lieutenant colonel, chief, standards activities branch, Signal Corps, United States Army, Red Bank, N. J.)

Are All the Basic Problems Solved in Electrical Machinery?

To the Editor:

I have read the article, "Are All the Basic Problems Solved in Electric Machinery?" by M. M. Liwschitz in the February 1944 issue of *Electrical Engineering*, page 47. I agree with the point he has made that there is still room for development and improvement of electric machines. I also agree with his concluding statements regarding the teaching of electric machinery, and I would like to point out that this method is not new. At the University of California the method outlined has been followed for the past 14 years, and we are firmly convinced that it is the shortest and most logical one.

THOMAS C. McFARLAND (M '32)

Chairman, department of electrical engineering, University of California, Berkeley)

TVA Releases Annual Report

To the Editor:

In the February issue of *Electrical Engineering*, page 73, is printed a current news item headed, "TVA Releases Annual Report," which reads:

A net income of $13,148,000 was returned to the United States Treasury from gross revenues of $31,670,000 accruing from the sale of electric power by the Tennessee Valley Authority. . . .

In a literal sense that statement undoubtedly is true, but its import or implications are very misleading. The United States Treasury is merely a depository of TVA's funds. It would be more accurate to say that TVA deposited $13,148,000 to its own credit in the United States Treasury. The implication of the statement is that TVA is paying some of its indebtedness to the Federal Government. That is not true as it has, so far, not paid one cent to the government in payment on its debt.

But that is not all that makes the report misleading. The taxpayers of the country paid last year at least $20,000,000 interest on TVA's indebtedness, and they also are paying the federal taxes that TVA and its contractors should be paying to aid in the prosecution of the war.

For example, the private utilities of Wisconsin paid 46 cents per kilowatt hour in taxes which is more than TVA's revenue per kilowatt hour. Much of this went to the federal government in the form of income taxes, excise taxes, and capital stock taxes. The Mississippi River Power Company also sells at wholesale, but that does not exempt it from taxes. In 1942 on a gross revenue of $6,000,000 it paid approximately $1,500,000 in taxes to the Federal Government whereas TVA on a revenue of $31,670,000 paid nothing.

C. M. JANSKY (F '32)

(Professor emeritus of electrical engineering, University of Wisconsin, Madison)

New Machine Produces 3,500 Jewels Daily

Developed by the Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa., after Switzerland the chief supplier of sapphires for industrial use, was blockaded by Germany, this automatic machine turns out substitute glass jewels at the rate of 3,500 per day. When the synthetic jewels first were produced it was necessary to manufacture them by hand at the rate of only 1,200 per day of which number many were imperfect. The jewels are an essential part of millions of electric instruments

NEW BOOKS • • •

The following new books are among those recently received from the publishers. Books designated ESL are available at the Engineering Societies Library; these and thousands of other technical books may be borrowed from the library by mail by AIEE members. The Institute assumes no responsibility for statements made in the following summaries, information for which is taken from the prefaces of the books. All inquiries relating to the purchase of any book reviewed in these columns should be addressed to the publisher of the book in question.

Power Unleashed. By M. M. Samuels. Dorset House, Inc., New York, N. Y., 1943. 300 pages, $5\frac{1}{4}$ by 8 inches, $3.50.

This descriptive story of the harnessing of the latent energy of the coal, oil, gas, and water and its transformation into safe and useful energy interprets the development and technical characteristics of electricity for the layman as well as the engineer. The ubiquity of electricity in modern life becomes apparent as the process of transporting power to the consumer is unfolded. Analogy between everyday occurrences familiar to the average layman and technical terms, structures, and reactions is used freely. The function of the engineer and probable future extensions of sources and uses of power are discussed.

Electronic Physics. By L. G. Hector, H. S. Lein and C. E. Scouten. Blakiston Company, Philadelphia, Pa., 1943. 355 pages, illustrated, $8\frac{1}{2}$ by $5\frac{1}{2}$ inches, cloth, $3.75. (ESL.)

The object of this text is to provide the beginner with a new approach to the subject. All electric phenomena are studied from the electron-proton point of view. Ordinary light, wireless, and X rays are shown to be closely related and to be various aspects of electric phenomena. Photoelectricity and electron tubes are presented as a unified part of the entire subject. Natural radioactivity and transmutation of elements are also considered in the light of the electric nature of atoms.

Principles and Applications of Electrochemistry, Volume 1. Principles. By H. J. Creighton. Fourth edition. John Wiley and Sons, New York, N. Y.; Chapman and Hall, London, England, 1943. 477 pages, illustrations, $8\frac{1}{2}$ by $5\frac{1}{2}$ inches, cloth, $5. (ESL.)

This well-known and popular presentation of the principles and general theory of electrochemistry has been entirely revised for this edition. A number of new topics has been introduced, old material has been deleted, and new tables of data have been included. The book is intended as a text for a systematic course of instruction and as a reference book. A large number of bibliographic footnotes are included.

Aircraft Electrical Engineering. By F. G. Spreadbury. Sir Isaac Pitman and Sons, London, England; Pitman Publishing Corporation, New York, N. Y., 1943. 272

pages, illustrated, 9 by 5½ inches, cloth, $6. (ESL.)

The various ways in which electricity is used in aircraft are presented with the needs of the designer in view. The chapters deal with ignition, ignition devices, generators and motors, uses of alternating current, voltage regulation, radio supply, ripple-smoothing circuits and ripple-voltage measurements, permanent magnets, and aircraft pyrometry.

Navigation. By L. M. Kells, W. F. Kern, and J. R. Bland. McGraw-Hill Book Company, Inc., New York, N. Y., and London, England, 1943. 479 pages, illustrated, 9 by 6 inches, cloth, $5. (ESL.)

This practical textbook begins with the fundamental mathematics for pilots and descriptions of the necessary instruments and their use. Piloting methods for coastal and inland waterways are next considered, together with navigation aids and rules. The latter half of the book is devoted to the principles and practice of celestial navigation as used to determine and direct ship movements. This latter section is also basically applicable to aerial navigation.

Industrial Chemistry. By W. T. Read. Third edition. John Wiley and Sons, New York, N. Y.; Chapman and Hall, London, England, 1943. 631 pages, illustrated, 8½ by 5½ inches, cloth, $5. (ESL.)

The major part of this book is devoted to authoritative information on chemical raw materials, processes and products, and on typical chemical engineering operations for many purposes. Separate chapters are included dealing with chemical organizations, sources of chemical information, chemical economics, and so forth. The purpose of this edition is to present, as far as possible, a picture of industrial chemistry as it was at the beginning of 1942.

Electric Circuits and Fields. By H. Pender and S. R. Warren. McGraw-Hill Book Company, Inc., New York, N. Y., and London, England, 1943. 534 pages, illustrated, 8½ by 5 inches, cloth, $4. (ESL.)

From an engineering viewpoint this textbook gives: a description of the more important effects commonly described as electric and magnetic phenomena; a statement in words and in mathematical formulas of the fundamental laws or principles governing the relations of these phenomena; and the application of these principles to some of the simpler problems connected with the generation, transmission, and utilization of electric energy.

Aircraft Annual 1944. Edited by D. C. Cooke. First annual edition. Robert M. McBride and Company, New York 3, N. Y., 1944. 288 pages, illustrated, 9½ by 6½ inches, cloth, $3. (ESL.)

This is the first of a series of annual reviews which will give a comprehensive account of current activities in aviation. The text is readable and nontechnical and is accompanied by a profusion of excellent illustrations. Among the topics considered are the work of the United States Army and Navy, the Doolittle Tokyo raid, the strategy of bombing, American air transport, and the manufacturing industry.

Diesel Locomotives. By J. Draney. American Technical Society, Chicago, Ill., 1943. 472 pages, illustrated, 8½ by 5½ inches, cloth, $4. (ESL.)

The mechanical equipment of Diesel-electric locomotives is described in detail, with specific instructions for operation and maintenance. Following the general principles of Diesel engines come several chapters on fuel injection, lubrication, governing, supercharging, and so forth. The remaining chapters deal severally with the important types of Diesel-electric locomotives currently in use. The electrical phases will be covered in a companion volume.

Geometry. By W. F. Kern and J. R. Bland. John Wiley and Sons, New York, N. Y.; Chapman and Hall, London, England, 1943. 152 pages, illustrated, 8¼ by 5 inches, cloth, $1.75. (ESL.)

This book presents the practical essentials of solid geometry. For the development of "space intuition" a large number of exercises call for visualization of cross sections of solids in connection with reducing a problem to a number of simple problems in plane geometry. Most of the problems and illustrative examples relate to familiar objects of everyday experience or to military and naval situations.

Intermediate Course in Differential Equations. By E. D. Rainville. John Wiley and Sons, New York, N. Y.; Chapman and Hall, London, England, 1943. 213 pages, tables, 8½ by 5 inches, cloth, $2.75. (ESL.)

This book is intended as a bridge for the gap between elementary courses and really advanced courses, and affords an introduction to several topics of importance in the classical theory. Specific topics covered include Riccati equations, the hypergeometric equation, equations of the Fuchsian type, confluence of singularities, and Whittaker's confluent hypergeometric equation.

Modern Airfield Planning and Concealment. By M. E. De Longe. Pitman Publishing Corporation, New York, N. Y., and Chicago, Ill., 1943. 167 pages, illustrated, 9½ by 6 inches, cloth, $4. (ESL.)

The problem of concealing airfields is discussed by a pilot with experience in camouflage. The distinctions between camouflage and concealment are pointed out, and methods, for building in maximum concealment are considered. Proper choice of airfield locations is treated. The book is intended to guide the construction of civil airfields as well as military ones.

Plastics Catalog 1944. Plastics Catalogue Corporation, 122 East 42nd Street, New York 17, N. Y., 989 pages, illustrated, 11½ by 8½ inches, cloth, $6. (ESL.)

The 1944 edition of the catalog is a compendium of information on materials, methods of engineering, molding, fabricating, finishing and assembling, and machinery and equipment. Other sections deal with laminates, plywood, vulcanized fiber, plastic coatings, synthetic fibers, rubber, and rubberlike plastics. There is a bibliography and also a directory of sources of materials and equipment.

Synthetic Resins and Rubbers. By P. O. Powers. John Wiley and Sons, New York, N. Y.; Chapman and Hall, London, England, 1943. 296 pages, illustrated, 8½ by 5½ inches, cloth, $3. (ESL.)

The purpose of this book is to describe briefly the chemistry of synthetic resinous materials and the raw materials from which they are made. The text is divided into the following general parts: theories of polymer formation; condensation polymers; vinyl polymers; synthetic rubbers (by K. H. Weber); resins from natural products; and application of synthetic resins.

This Fascinating Lumber Business. By S. F. Horn. Bobbs-Merrill Company, Indianapolis, Ind., and New York, N. Y., 1943. 328 pages, illustrated, 9 by 6 inches, cloth, $3.75. (ESL.)

All phases of our lumber industry are given consideration in this informative volume. Lumbering in the West and the South, the manufacture of lumber and other forest products, methods of distribution, and the economics of the industry are discussed. Other chapters treat of warfare uses of lumber, methods of wood preservation, timber engineering, and so forth.

Maintenance Arc Welding. James F. Lincoln Arc Welding Foundation, Cleveland, Ohio, 1943. 234 pages, illustrated, 9 by 6 inches, cloth, 50 cents in the United States; 75 cents, foreign. (ESL.)

This volume contains 25 papers which consider the uses of arc welding in maintenance work, as a means of reclaiming broken and worn equipment and fabricating replacements. Each paper discusses work in a specific plant, describing what was done, methods, and costs.

PAMPHLETS . . . .

The following recently issued pamphlets may be of interest to readers of "Electrical Engineering." All inquiries should be addressed to the issuers.

Guide to Cost Study in Corporation Postwar Planning. National Association of Manufacturers, 14 West 49th Street, New York 20, N. Y., 26 pages.

Guide to Postwar Product Development. National Association of Manufacturers, 14 West 49th Street, New York 20, N. Y., 14 pages.

Physical Fitness in Industry. Committee on Physical Fitness, Federal Security Agency, 1025 Vermont Avenue N.W., Washington 25, D. C., 15 pages.

Care and Maintenance of Electrical Equipment. Square D Company, 6060 Rivard Street, Detroit 11, Mich., 28 pages, no charge.

Preventing and Correcting Low Power Factor. George S. May Business Foundation, 111 South Dearborn Street, Chicago 3, Ill., 6 pages.

Men, Minutes, and Victory. Division of Labor Standards, United States Department of Labor, Washington 25, D. C., no charge.

TRANSACTIONS SECTION

Preprint of Corresponding Pages From the Current Annual AIEE Transactions Volume

Calculation of Unbalanced Voltage Drops in Distribution Circuits With Particular Reference to Multi-grounded Neutrals

W. R. BULLARD MEMBER AIEE H. L. LOWE MEMBER AIEE H. W. WAHLQUIST MEMBER AIEE

PREWAR economic conditions necessitated the use of increasingly precise engineering technique in the design of electric distribution systems. Present wartime demands for conservation of materials have intensified the need for such technique. Control of voltage regulation is a factor of major importance in determining the capital investment in conductors and accessory materials needed for distribution circuits. However, an important hindrance to the application of accurate engineering in taking account of this factor has been the lack of a simple method of calculating voltage drops in circuits having unbalanced conductor impedances and unbalanced loads. The method of symmetrical components, used mainly for calculation of unbalanced fault currents and for solution of a wide variety of problems involving circuit unbalances, has not been accepted generally as a sufficiently rapid method for the solution of voltage-drop problems commonly encountered in distribution-engineering work. Furthermore, simple methods ordinarily used, which neglect unbalanced conditions, often give totally inaccurate and misleading results.

This paper presents the elements of a simplified method applicable particularly to circuits, such as those having multi-grounded neutrals, in which phase-to-neutral mutual impedances differ materially from phase-to-phase mutual impedances, but in which the spacings in each of the two groups do not differ greatly from each other. This method provides for the combination of the effects of self- and mutual-impedances, so that calculation of voltage drops is reduced basically to a single vector multiplication of a current and an impedance for each phase conductor, and for the earth–neutral combination treated as a single conductor. The change in circuit voltage produced by these drops then can be determined by vector additions and subtractions.

In practical application the entire process is reduced to simple algebra by use of the familiar method of approximation in which the expression ($IX \sin q + IR \cos q$) is used to represent the arithmetical change in voltage at the load due to drop along the conductors. In this expression all quantities are scalar, I representing load current, X representing conductor reactance, R representing conductor resistance, and q representing the angle between load current and the particular circuit voltage under consideration at the receiving end.

Algebraic working equations may be written for various commonly encountered circuit conditions, using as a basis the vector equations developed in this paper. In combination with working impedance data prepared in accordance with the relations shown in the paper, such algebraic equations may be used for the rapid determination of delivered voltage in distribution circuits involving any type and size of conductor.

Fundamental vector equations are developed in the following, and examples of working algebraic equations and working impedance data are given.

General Equations

With reference to Figure 1, which symbolizes a four-wire three-phase circuit with multigrounded neutral, the voltage drop $\boldsymbol{V_A}$ in the circuit composed of conductor A and earth return corresponds to the vector difference between source voltage $\boldsymbol{E_A}$ and load voltage $\boldsymbol{E_A'}$, as measured to an equivalent earth return plane of reference. The voltage drop $\boldsymbol{V_A}$ is a quantity not obtainable by direct practical measurement but is employed as a basis for writing expressions for general equations. Equations for $\boldsymbol{V_A}$ and for the voltage drops in other conductors can be written as follows:

$$V_A = E_A - E_A' = L(I_A Z_{AA} + I_B Z_{AB} + I_C Z_{AC} + I_N Z_{AN}) \text{ volts} \quad (1)$$

$$V_B = E_B - E_B' = L(I_A Z_{AB} + I_B Z_{BB} + I_C Z_{BC} + I_N Z_{BN}) \quad (2)$$

$$V_C = E_C - E_C' = L(I_A Z_{AC} + I_B Z_{BC} + I_C Z_{CC} + I_N Z_{CN}) \quad (3)$$

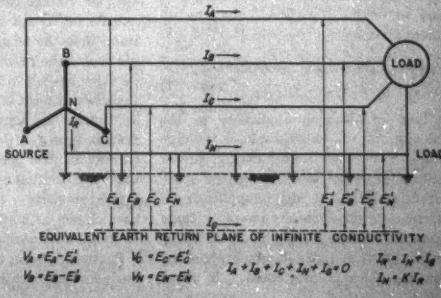


Figure 1. Three-phase four-wire circuit with multi-grounded neutral

Paper 44-54, recommended by the AIEE committee on power transmission and distribution for presentation at the AIEE winter technical meeting, New York, N. Y., January 24-28, 1944. Manuscript submitted November 12, 1943; made available for printing December 17, 1943.

W. R. BULLARD, H. L. LOWE, and H. W. WAHLQUIST are all electrical engineers with Ebasco Services, Inc., New York, N. Y.

$$V_N = E_N - E_{N'} = L(I_A Z_{AN} + I_B Z_{BN} + I_C Z_{CN} + I_N Z_{NN}) \quad (4)$$

$$I_A + I_B + I_C + I_N + I_G = 0 \quad (5)$$

where bold-face characters indicate vector quantities, and

I_A, I_B, and I_C = currents in conductors A, B, and C, respectively, in amperes

I_N and I_G = averaged currents in the neutral conductor and in the earth, respectively, in amperes

Z_{AA}, Z_{BB}, Z_{CC}, and Z_{NN} = self-impedances of conductors, A, B, C, and N, respectively, with earth return, in ohms per mile

Z_{AB}, Z_{AC}, and so forth = mutual impedances between conductors A and B, and conductors A and C, and so forth, with earth return, respectively, in ohms per mile

Z_{AN}, and so forth = mutual impedance between conductor A and the neutral conductor N, with earth return, and so forth, in ohms per mile

L = length of circuit in miles

Voltage Drop Phase-to-Phase

$$V_{AB} = V_A - V_B = I_A(Z_{AA} - Z_{AB})L - I_B(Z_{BB} - Z_{BA})L + I_C(Z_{AC} - Z_{BC})L + I_N(Z_{AN} - Z_{BN})L \text{ volts} \quad (6)$$

Equation 6, for calculating phase-to-phase voltage drops under any condition of unbalanced impedances, contains a term with a multiplier I_N, namely $I_N \times (Z_{AN} - Z_{BN})L$. In this form the equation is not directly usable for a circuit having multigrounded neutral, because the value of I_N is not readily obtainable. However, if it is assumed that phase-to-neutral spacings are equal, the term in question disappears, because the impedance quantities within the bracket then are equal to each other. The quantities $(Z_{AA} - Z_{AB})$, $(Z_{BB} - Z_{BA})$, and so forth, represent positive-phase-sequence impedances as published in handbook tables and can be represented more simply by the symbols $Z_A{}^B$, $Z_B{}^A$, and so forth, indicating positive-phase-sequence impedance of conductor A at spacing AB, positive-phase-sequence impedance of conductor B at spacing BA, and so forth. Equation 6 may be reduced then to

$$V_{AB} = I_A Z_A{}^B L - I_B Z_B{}^A L + I_C(Z_C{}^B - Z_C{}^A)L \text{ volts} \quad (7)$$

This equation is applicable to the calculation of phase-to-phase voltage drops in circuits having multigrounded neutrals in which phase-to-neutral spacings are equal. It also is applicable to calculation of phase-to-phase voltage drops in circuits having ungrounded or unigrounded neutrals in which phase-to-neutral spacings are equal. If these spacings are unequal, the resulting error in assuming phase-to-neutral spacings equal to the "geometric mean" will be negligible, unless conductors are large in size and phase-to-neutral spacings differ greatly. All equations in this paper for circuits involving multigrounded neutrals are dependent on the foregoing simplifying assumption, since the improvement in accuracy is not deemed to justify the complexity of rigorous calculations involving unequal phase-to-neutral spacings. This is particularly true, since the type of conductor arrangement usually encountered in connection with circuits having multigrounded neutrals is that in which the neutral position is some distance below and centered under the phase conductors. In such arrangements the proportional differences between individual line-to-neutral spacings usually are very small. If phase-to-phase spacings are assumed equal, the last term of equation 7 disappears, and the calculation reduces to a single vector product for each conductor.

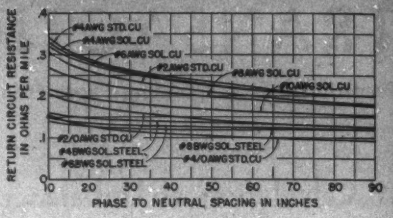


Figure 2. Return-circuit resistance for multigrounded circuits with zero-resistance grounds

Voltage Drop Phase-to-Neutral

$$V_{AN} = V_A - V_N = I_A(Z_{AA} - Z_{AN})L - I_N(Z_{NN} - Z_{AN})L + I_B(Z_{AB} - Z_{BN})L + I_C(Z_{AC} - Z_{CN})L \quad (8)$$

This may be reduced, if single symbols are used to represent positive-phase-sequence impedance, to

$$V_{AN} = I_A Z_A{}^N L - I_N Z_N{}^A L + I_B(Z_B{}^N - Z_B{}^A)L + I_C(Z_C{}^N - Z_C{}^A)L \quad (9)$$

This equation gives a general expression for voltage drops in multigrounded circuits but is not directly usable in this form, since the term I_N represents only a portion of the residual load current, and its value has yet to be determined. Furthermore, it must be kept in mind, in the application of formulas for this case, that the term I_N is defined as the averaged current in the neutral conductor, and that the mutual-impedance terms are defined similarly. These definitions have been chosen to simplify the development of equations suitable for practical use.

Further assumptions also may be made for simplification of equations without much sacrifice in accuracy. These assumptions are:

(*a*). Uniform resistance of grounding electrodes, taken as an average of the resistance of individual grounds.

(*b*). Uniform spacing between grounding electrodes along the line, taken as an average of actual spacings.

(*c*). Uniform resistivity of the earth.

(*d*). Symmetrical arrangement of phase conductors with respect to the neutral conductor. (In cases where this symmetry does not exist, the simplification using geometric mean spacing gives negligible error, unless the three phase-to-neutral spacings are widely different, and conductors are large.)

If these assumptions are used, an equation for I_N in terms of I_R and various calculable impedances has been derived from data developed by the Joint Subcommittee on Development and Research, Edison Electric Institute and Bell Telephone System.[1] The derived equation may be written as follows:

$$I_N = \frac{Z_{AN}}{Z_{NN}} \left(\frac{Z_{NN} - Z_{AN}\,u}{Z_{NN} - Z_{AN}} \right) I_R = K I_R \quad (10)$$

where

$I_R = I_N + I_G$ = total residual current in amperes, equal to the total return circuit current in the parallel path of the neutral conductor and earth. This current is a fixed vector value for a given condition of loading

I_N = averaged current in the neutral conductor in amperes (as previously defined) and is also fixed for given circuit and loading conditions

I_G = averaged current in the earth in amperes and is fixed for given circuit and loading conditions

u = a factor which takes into account the number and average resistance of the grounding electrodes installed along the line and the terminal grounding conditions. Its value is as follows for a circuit with neutral conductor connected at the source end to a station ground of zero ohm resistance and grounded along its length by grounds of finite resistance, the load being connected at the end of the circuit

$$u = 1 - \left(\frac{Z_{AN} - Z_{NN}}{Z_{AN}} \right) \frac{1}{\theta L} \tanh(\theta L)$$

($u = 1$ for zero-resistance grounds)

$$\theta = \sqrt{\frac{Z_{NN}}{R_G}}$$

R_G = averaged resistance of the grounding electrodes divided by the average number of grounds per mile

Z_{AN} = mutual impedance between conductor A and the neutral, with earth return, in ohms per mile

Z_{NN} = self-impedance of the neutral conductor, with earth return, in ohms per mile

L = length of line from source to load in miles

$$K = \frac{Z_{AN}}{Z_{NN}}\left(\frac{Z_{NN} - Z_{AN}u}{Z_{NN} - Z_{AN}}\right)$$

($K = 1$ for ungrounded or unigrounded neutral)

If the expression KI_R is substituted in equation 9 for I_N, and if the general superscript NP is used for the line-to-neutral spacing, equation 9 may be written as follows for a multigrounded circuit:

$$V_{AN} = I_A Z_A{}^{NP} L - I_R Z_N{}^{NP} KL + I_B(Z_B{}^{NP} - Z_B{}^{A})L + I_C(Z_C{}^{NP} - Z_C{}^{A})L \text{ volts} \quad (11)$$

This is a general equation for calculating phase-to-neutral voltage drops in any three-phase four-wire multigrounded circuit in which line-to-neutral spacings can be assumed equal, or where these spacings are taken as the geometric mean phase-to-neutral spacings. It applies to lines involving any size or kind of wire for any of the phase or neutral conductors, and to those involving finite resistances of grounding electrodes. It also applies for circuits involving zero-resistance grounds, or ungrounded or unigrounded neutrals, if the values of u and K are determined correctly.

When phase-to-phase spacings are assumed to be equal, in addition to the assumption of equal phase-to-neutral spacings, an expression for phase-to-neutral voltage drops in multigrounded circuits may be developed, as follows:

If the expression

$$\frac{Z_{AN}}{Z_{NN}}\left(\frac{Z_{NN} - Z_{AN}u}{Z_{NN} - Z_{AN}}\right) I_R \text{ is substituted for } I_N$$

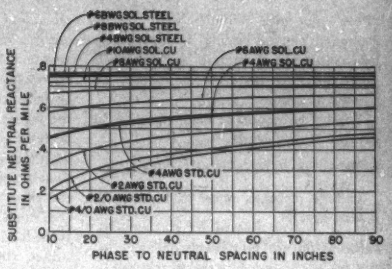
equation 8 may be written

$$V_{AN} = I_A(Z_{AA} - Z_{AN})L - \frac{Z_{AN}}{Z_{NN}}\left(\frac{Z_{NN} - Z_{AN}u}{Z_{NN} - Z_{AN}}\right)(Z_{NN} - Z_{AN})I_R L + I_B(Z_{AB} - Z_{BN})L + I_C(Z_{AC} - Z_{CN})L$$

When the terms are cancelled, this equation may be reduced to

$$V_{AN} = I_A(Z_{AA} - Z_{AN})L - \left(Z_{AN} - \frac{Z_{AN}{}^2 u}{Z_{NN}}\right) I_R L + I_B(Z_{AB} - Z_{BN})L + I_C(Z_{AC} - Z_{CN})L \quad (12)$$

Figure 3. Substitute neutral reactance for multigrounded circuits with zero-resistance grounds



Since phase-to-neutral spacings are assumed to be equal, and phase-to-phase spacings also are assumed to be equal, the terms $(Z_{AB} - Z_{BN})$ and $(Z_{AC} - Z_{CN})$ are equal to each other and also equal to $(Z_{AB} - Z_{AN})$.

If this expression is substituted subscripts and superscripts are changed, and $I_B Z_{AA} L$ and $I_C Z_{AA} L$ are added and subtracted, equation 12 becomes

$$V_{AN} = I_A Z_A{}^N L - \left(Z_{PN} - \frac{Z_{PN}{}^2 u}{Z_{NN}}\right) I_R L + (I_B + I_C)(Z_A{}^{NP} - Z_A{}^P)L \quad (13)$$

Since

$$I_A + I_B + I_C + I_N + I_G = 0$$

and

$$I_N + I_G = I_R$$

$$I_A + I_B + I_C = -I_R$$

and

$$I_B + I_C = -(I_A + I_R)$$

Substituting

$$-(I_A + I_R)$$

for

$$(I_B + I_C)$$

equation 13 reduces to

$$V_{AN} = I_A(Z_A{}^{NP} + Z_A{}^P - Z_A{}^{NP})L - I_R\left[\left(Z_{PN} - \frac{Z_{PN}{}^2 u}{Z_{NN}}\right) + Z_A{}^{NP} - Z_A{}^P\right]L$$

or

$$V_{AN} = I_A Z_A{}^P L - I_R\left[\left(Z_{PN} - \frac{Z_{PN}{}^2 u}{Z_{NN}}\right) + Z_A{}^{NP} - Z_A{}^P\right]L$$

or

$$V_{AN} = I_A Z_A{}^P L - I_R\left[\left(Z_{AA} - \frac{Z_{PN}{}^2 u}{Z_{NN}}\right) - Z_A{}^P\right]L \quad (14)$$

A convenient name for the bracketed expression in the preceding equation is "substitute neutral impedance," and it may be represented by the symbol Z_{SN} as follows:

$$V_{AN} = I_A Z_A{}^P L - I_R Z_{SN} L \text{ volts} \quad (15)$$

Similarly

$$V_{BN} = I_B Z_B{}^P L - I_R Z_{SN} L$$

and

$$V_{CN} = I_C Z_C{}^P L - I_R Z_{SN} L$$

Thus, by using two simplifying assumptions, namely, phase-to-phase spacings are equal, and phase-to-neutral spacings are equal, the calculation of phase-to-neutral voltage drop reduces to a simple vector multiplication of a current and an impedance for the phase conductor and a current and impedance for the return parallel path composed of neutral and earth.

Equation 15 may be used to calculate voltage drops in single-phase and in open-wye circuits in addition to three-phase circuits for which the equation is developed.

Reduction to Algebraic Approximations

As examples of reduction of these equations to algebraic working form by the method of approximation mentioned in the introduction, formulas for line-to-neutral voltage change in a three-

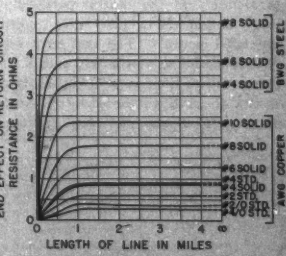


Figure 4. End effect on return-circuit resistance with finite-resistance grounds

$R_G = 1$

phase four-wire circuit with multigrounded neutral having a single-phase load connected from line A to neutral, phase sequence being A, B, C, may be written as follows:

Voltage reduction at load, phase A to neutral, is very nearly

$$I_A \cos\phi(R_A+R_E)+I_A \sin\phi(X_A{}^P+X_{SN})$$

Voltage increase, phase B to neutral, is very nearly

$$I_A R_E \cos(60°+\phi)+I_A X_{SN} \sin(60°+\phi)$$

Voltage increase, phase C to neutral, is very nearly

$$I_A R_E \cos(60°-\phi)-I_A X_{SN} \sin(60°-\phi)$$

In these expressions all quantities are scalar and

R_A = total resistance of conductor A
R_E = total return circuit resistance, or resistance of earth-neutral combination
$X_A{}^P$ = total handbook reactance of conductor A at phase-to-phase spacing
X_{SN} = total substitute neutral reactance of the circuit
ϕ = power-factor phase angle of the load current with respect to load voltage

Substitute Neutral Impedance

The bracketed expression for Z_{SN} in equation 14 can be reduced to the form

$$Z_{SN}=Z_{AP}-\frac{Z_{AN}{}^2}{Z_{NN}}+\frac{(Z_{NN}-Z_{AN})^2}{Z_{NN}\Theta L}\tanh(\Theta L) \qquad (16)$$

In this expression, if resistance of connections to ground is assumed equal to zero, Θ becomes infinite, and the term $(Z_{NN}-Z_{AN})^2/(Z_{NN}\Theta L)\tanh(\Theta L)$ disappears. The first two terms, therefore, represent conditions under which the division of current between neutral and earth is determined only by self- and mutual impedances of phase and neutral conductors and the resistivity of the earth itself. Such conditions exist approximately in the central portions of long untapped circuits with multigrounded neutrals. The last term represents conditions at the load end of the circuit, where the escape of current from neutral to earth is retarded by resistance of ground connections, zero-resistance grounding conditions at the source and being assumed in the derivation of the equation in this particular form. For convenience, the last term of equation 16 is called "end effect." It is greater, the higher the resistance of ground connections. If grounding conditions are no better at the source end of the circuit than along its length, then an additional end effect must be inserted for the source end, doubling the value of the last term. If the load is not located at the end of the circuit, then two end effects in parallel relation must be taken into account, since current will flow in the neutral in both directions from the load.

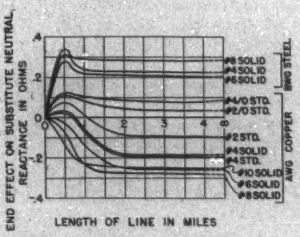


Figure 3. End effect on substitute neutral reactance with finite-resistance grounds

$R_G=1$

It has been customary in calculation of fault currents by the method of symmetrical components to neglect end effects and make calculations under the assumption that ground connections have zero resistance. This often results in negligible error, especially in the case of long circuits, such as transmission lines. However, in the case of voltage-drop calculations in distribution circuits, omission of end effects frequently will result in large error.

For use in practical engineering work, end effects and the other component of Z_{SN} composed of the first two terms of the expression in equation 16 can be calculated to cover a typical range of conductor types and sizes and incorporated in tabular or chart form, for example, as shown in Figures 2, 3, 4, and 5. Figures 2 and 3 give return circuit resistance and substitute neutral reactance for the first two terms of the expression, respectively, for various conductor types, sizes, and spacings. Figures 4 and 5 give resistance and reactance end effects for various conductors but for a particular value of R_G or resistance of ground connection per mile. A series of such charts for various values of R_G has been prepared as working data for practical application of the method.

In Figures 4 and 5 the last term of equation 16 has been multiplied by L, and total values are read directly opposite circuit lengths. In Figures 2 and 3 the values are unit values per mile and must be multiplied by the length of circuit before substitution in working formulas.

For the construction of the charts of Figures 2, 3, 4, and 5, the following physical constants were used as reasonably typical of conditions likely to be met in practice:

Earth resistivity.....50 meter ohms
Distance from conductors to image....2,000 feet
Conductor temperature.....65 degrees centigrade
Frequency.....60 cycles
Phase-to-phase spacing.....40 inches
(Deviations from this value ordinarily encountered have relatively little effect on accuracy)
Steel conductors.....high-tensile strength
Current intensity.....10 amperes per conductor

Circuits With Ungrounded Neutrals

The foregoing material has been confined to circuits with multigrounded neutrals, but the method is applicable to circuits with ungrounded or unigrounded neutrals by suitable modification of the expression for Z_{SN}. For such circuits this is found to be

$$Z_{SN}=(Z_N{}^{NP}+Z_A{}^{NP}-Z_A{}^P) \qquad (17)$$

These are all positive-phase-sequence impedances readily obtainable from handbook tables.

Reference

1. ENGINEERING REPORTS, volume IV, Joint Subcommittee on Development and Research, Edison Electric Institute, Bell Telephone System. Engineering report 37, COMPUTATION OF ZERO-SEQUENCE IMPEDANCES OF POWER LINES AND CABLES. Page 314, equations 1–3.

Overloading of Transformers—Cases Not Covered by the General Rules

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Synopsis: The general relations covering the heating of transformers and the effects of this heating on safe overloads are simple in principle, but the mathematics involved are complex. When suitable curves are used to express the relations, the simplicity is evident. Loading of transformers and other equipment by temperature is increasingly common and rightly so. An understanding of the principles involved aids in intelligent application of information for loading by temperature. The usefulness of the American Standard *C57.3*, "Guides for Operation of Transformers and Regulators," 1942 would be increased by the inclusion of temperature-time charts so that a solution may be obtained for the unusual loading case. These charts are based on the same principles on which the present rules are based. In addition to simplifying the procedure for taking care of special cases, such charts present a graphic picture of the heating relations of transformers.

THE American Standard "Guides for Operation of Transformers and Regulators" *C57.3*, 1942 and the interim reports on overloading (references 21 and 24) give information which covers many of the overloading conditions encountered with transformers. These rules, however, do not cover every situation. In order to help fill this lack, charts have been prepared which will enable the safety of practically any special case of loading to be determined.

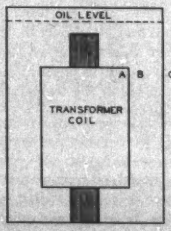

Figure 1. Oil-immersed transformer

Paper 44-66, recommended by the AIEE committee on electrical machinery for presentation at the AIEE winter technical meeting, New York, N. Y., January 24-28, 1944. Manuscript submitted September 10, 1943; made available for printing December 21, 1943.

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In addition to such quantitative values, there is also a need for a qualitative summation of the general principles on which transformer loading is based. Such a summation will aid in correct application of the rules and result in confidence that the application is correct. The general principles are outlined after which their application to specific cases is demonstrated by the use of charts.

General Principles

A familiar operation like heating water on a stove includes all the elements involved in heating and cooling of transformers. When a teakettle of cold water is placed on a stove, the water heats slowly because of its high thermal capacity. The heat given off by the hot gases of the fire must be transmitted to the water, which absorbs heat and increases its temperature. At all times, the temperature of the fire is higher than the temperature of the water, and heat flows from the fire to the water.

After the teakettle is removed from the fire the water remains hot for a considerable time. During this period, its temperature gradually decreases as the water loses heat to the surrounding air.

In a transformer, heat is generated in the copper of the windings and in the iron core. The transformer starting cold, a portion of this heat is absorbed by the copper because of its thermal capacity, and a portion of the heat is transferred to the oil. The oil, in turn, absorbs heat because of its thermal capacity, and, after its temperature increases, dissipates heat to the cooling medium, usually the air surrounding the transformer. In Figure 1 the flow of heat is from the copper at *A* to the oil at *B* and, in turn, from the oil at *B* to the air at *C*. The temperature difference between the copper at *A* and the adjacent oil at *B* is commonly called the copper "gradient." The difference in temperature between the oil at *B* and the air at *C* is commonly called the "oil rise" in temperature. If *A* is the copper adjacent to the hottest oil *B*, the copper temperature of *A* will be the hot-spot copper temperature, and the temperature difference between *A* and *B* will be hot-spot copper gradient. Since the temperature of the hottest spot of the copper is the temperature which controls permissible loading, the charts used in this paper are the charts of hot-spot temperature.

The rate at which insulation deteriorates depends upon the temperature, an increased temperature causing an increased rate of insulation deterioration. It is assumed that continuous temperature of 95 degrees centigrade hot-spot temperature of the copper will result in satisfactory length of life for a transformer. If the operating temperature is below 95 degrees centigrade for part of the time, it can be allowed to be above 95 degrees centigrade for part of the time and still secure the same transformer life. If advantage of this fact is taken, higher loads and higher temperatures can be permitted for short periods of operation. If the transformer is cool when the overload is applied, advantage may be taken of the thermal capacity of the transformer material, and higher overloads with a corresponding higher rate of heat generation can be permitted when the transformer is cool than when it is hot.

Heating and Cooling Curves

Quantitative variations of transformer temperatures with time can be shown conveniently on curves such as Figure 2. The rate of temperature rise with time depends upon the load upon the transformer.

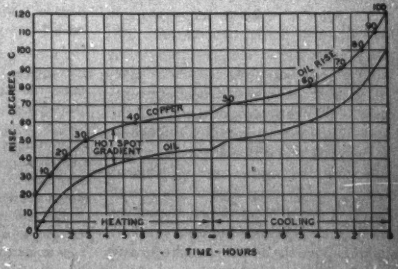

Figure 2. Heating and cooling curves for a typical power transformer carrying full load

Rises shown are hot-spot copper and top oil rise above ambient air temperature

The curves of Figure 2 have been drawn for 100 per cent load. The left-hand part of the oil curve of Figure 2 shows how the temperature of the oil increases with time as load is applied to the transformer starting cold. The right-hand part of the oil curve shows the manner in which the oil temperature decreases when the starting temperature is higher than the final temperature of the oil. Figure 2 is really two sets of curves in one, the left-hand side of the chart being the curves for increasing copper and oil temperature and the right-hand side of the chart being the curves of decreasing copper and oil temperature. The side of the chart to be used is not determined arbitrarily but is determined by the oil-temperature rise. If the oil rise is above 45 degrees centigrade at the start of the period of time considered, the starting temperature and, consequently, the starting time will fall on the right-hand side of the chart. For example, if the starting oil-temperature rise were 55 degrees centigrade, the starting time would be six hours on the cooling or right-hand side of the chart. If, however, the starting oil-temperature rise were 35 degrees centigrade, the starting time would be four hours on the left-hand side of the chart. In either case, as time elapses the numerical value of the time in hours would increase.

As shown by the left-hand side of Figure 2, when a cold transformer is loaded, the oil temperature rises rapidly almost as a straight line because practically all of the heat generated is absorbed by the copper and iron and oil of the transformer. If no heat-dissipating surface were supplied, the temperature would increase in a straight line indefinitely until failure occurred. After a time the curve of oil-temperature rise departs from a straight line as more heat is dissipated to the surrounding air. After several hours the rate of increase in temperature is very slow, until finally all of the heat generated is being dissipated to the air and the oil temperature no longer increases.

The right-hand side of Figure 2 shows how the oil temperature decreases with time when the ultimate temperature is lower than the initial temperature. The rate of decrease in temperature is most rapid at the beginning near zero time. The rate of decrease in temperature becomes slower with lapse of time, until the same ultimate temperature is reached as for the same load with rising temperature.

Because the copper-over-oil gradient changes rapidly compared to the rate of change of the oil temperature, the copper temperature is assumed to be a constant amount above the oil temperature for any load by the value of the gradient of the transformer, and the copper curve is drawn accordingly. If the oil rise of the transformer is known (as by reading the thermometer on the transformer case) and 100 per cent load is applied, the temperature rise from that time on can be determined from the curve by assuming that the starting time is the time corresponding to the starting oil temperature. If, for example, it is assumed that the starting oil temperature is 30 degrees centigrade, the starting time would be 2.8 hours as read from the oil curve corresponding to 30 degrees centigrade. The transformer does not know whether the 30 degrees centigrade was obtained by carrying 100 per cent load starting cold or by cooling down from a higher temperature. Consequently, it may be assumed for purposes of calculation that the 30-degree-centigrade rise was obtained following the 100 per cent load curve, the load being applied when the transformer was cold. If this load of 100 per cent is carried for two hours, the total time will be 2.8 plus 2 = 4.8 hours. The copper temperature rise at the end of 4.8 hours will be 58 degrees centigrade as read on the copper curve. Each point on the copper curve corresponds to a definite oil temperature on the oil-temperature curve. Accordingly, it is possible to dispense with the oil curve and use only the copper curve if the points on the copper curve are labeled with figures as shown in Figure 2.

Accordingly, for an initial oil temperature of 30 degrees centigrade and 100 per cent load, the starting point on the copper curve is the point marked 30, corresponding to a time of 2.8 hours. Two hours later at a time of 4.8, the copper-temperature rise is read as 58 degrees and the corresponding oil temperature can be estimated as 38 degrees by interpolating between the 30- and 40-degree marks on the copper curve, or by subtracting the known gradient of 20 degrees centigrade. The same general principles apply not only to transformers but also to other types of electrical equipment where thermal characteristics are a factor in determining the safe load which can be carried.

Use of Temperature–Time Chart

Figure 3 consists of curves similar to Figure 2 for 0, 60, 80, 100, 120, 140, 160, 180, and 200 per cent loads for the hot-spot-temperature rise above the ambient air. They were drawn in exactly the same manner as the copper curve of Figure 2. The dotted lines are drawn through points of equal oil temperatures. The oil temperature values are indicated by the figures at each end of the dotted lines.

The purpose of the curves of Figure 3 is not solely to secure a chart by which temperature values can be calculated readily. It has the advantage of presenting the various factors of time, per cent load, and rise in degrees centigrade in such a manner that the physical phenomena may be followed. For example, the curve for 120 per cent load is a curve of the temperature rise of the hot-spot copper above the surrounding air versus time when a transformer is carrying 120 per cent load. The dotted lines merely represent a simple means of indicating the oil temperature on each curve corresponding to the given copper temperature. As stated, the purpose of the chart is not only to determine temperature values for given load cycles but also to present a physical picture of the rise and fall of the temperature during the load cycle.

Example

If the initial oil-temperature rise is 30 degrees centigrade, what will the temperature be at the end of the time

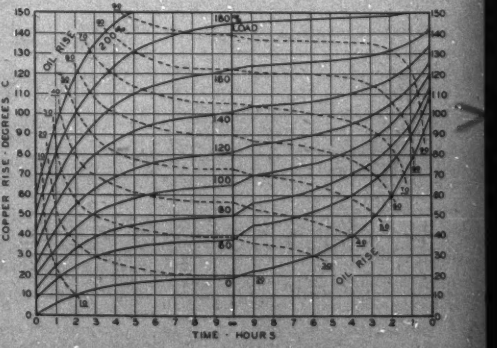

Figure 3. Heating and cooling curves for a typical transformer for various loads for the following full-load values: Hot-spot gradient, 20 degrees centigrade; oil rise, 45 degrees centigrade; ratio of copper loss to iron loss, two; thermal time constant, three hours. Rises shown are hot-spot copper and top oil rise above ambient-air temperature

Table I

Per Cent Load	Time (Hours) Elapsed	Start-ing	Final	Final Hot-Spot Copper Rise	Final Copper Temperature With 10 Degrees Centigrade Ambient
100	2	2.8	4.8	58	68
140	1	2.2	3.2	82	92
80	1	6.6	7.6	58	68

when 100 per cent load is carried for two hours followed by 140 per cent load for one hour followed by 80 per cent load for one hour? Is this a safe loading condition where the ambient temperature is ten degrees centigrade?

In Figure 3, the time corresponding to 30-degree-centigrade oil rise on the 100 per cent load curve is 2.8 hours; 2.8 hours plus two hours equals 4.8 hours. The copper-temperature rise corresponding to 4.8 hours on the 100 per cent load curve is 58 degrees centigrade. Moving to the 140 per cent load curve, keeping parallel to the dotted lines, one determines the time of 2.2 hours as being the starting time corresponding to the same oil-temperature rise (38 degrees centigrade) as for the finish of the preceding run; 2.2 hours plus one hour equals 3.2 hours. The copper-temperature rise corresponding to 3.2 hours on the 140 per cent load curve is 82 degrees centigrade which is the copper-temperature rise at the end of that time. Again moving parallel to the dotted lines, one finds the starting time for the 80 per cent load curve to be 6.6 hours. Adding 6.6 hours plus one hour equals 7.6 hours. The copper-temperature rise corresponding to 7.6 hours on the 80 per cent load curve is 58 degrees centigrade. By interpolation between the dotted curves, this corresponds to a 44-degree-centigrade oil temperature. For convenience in calculation, these values are arranged in Table I.

Since the hot-spot (copper) temperature is below 95 degrees centigrade at all times, it is obvious that the loads described in Table I may be carried with safety.

Any load cycle can be traced through the curves in similar manner, and the oil and copper temperature at any point on the cycle may be readily determined. In addition, at any point on the cycle the effect of increased time may be determined, since, by inspection, it is obvious whether further increase in time will greatly increase or decrease the rise obtained.

The chart of Figure 3 can, of course, be drawn with other variables plotted on the horizontal and vertical axis, or by means of nomograms or special slide rules. The

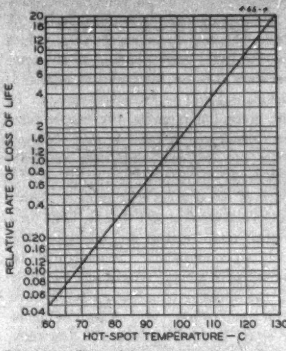

Figure 4. Rate of loss of life of transformer insulation in terms of rate of loss of life at 95 degrees centigrade

arrangement of Figure 3, however, produces a better physical picture for most practical cases.

The curves of Figure 3 have been drawn for the following transformer characteristics at 100 per cent load: a ratio of copper loss to iron loss of two to one, a hot-spot copper gradient above the oil of 20 degrees centigrade, an ultimate oil rise above the ambient air of 45 degrees centigrade, and a thermal time constant of three hours. Many modern power transformers have characteristics which are approximately the same as these assumed values, and the curves of Figure 3 can be used for such transformers.

Some transformers, particularly older transformers, may have higher gradients and shorter time constants than those used to determine the curves of Figure 3. The chart of Figure 5 has been drawn for use on such transformers with lower overload capabilities, assuming the following full-load values: a hot-spot gradient of 30 degrees centigrade, oil rise 35 degrees centigrade, ratio of copper loss to iron loss at full load 2 to 1, thermal time constant two hours. For general use either the charts of Figure 3 or the chart of Figure 5 will be used, whichever is closer to the characteristics of the actual transformer. In case of doubt Figure 5 should be used.

The use of typical charts and the use of typical values of constants for determining permissible overloads of transformers follow the general principles which are used in preparing other guides for operation of transformers, such as American Standard C-57.3. When this section on the guides for operation of transformers is revised, charts such as Figure 3 or Figure 5 or both would add useful information. If other values than those assumed for Figures 3 and 5 are chosen for the other data, these figures can be revised, using the same constants as are used for the other rules. Detailed means by which curves of Figures 2, 3, and 5 may be obtained are described in reference 20 (see the appendix).

For any particular transformer, values of hot-spot copper gradient and top oil rise at full load, and the thermal time constant (the time which would be required for the transformer oil to reach its ultimate temperature if all the heat were absorbed in the oil and no heat were dissipated to the air) may be obtained from the transformer manufacturer. For more accurate results, of course, charts similar to Figures 3 and 5 may be constructed especially for a particular transformer, but this refinement is seldom necessary.

Calculation of Loss of Life of a Transformer

The curves of Figures 3 and 5 can be used to calculate allowable loads and the loss of life for a given loading cycle. The loss of life for a given loading cycle can be calculated from Figure 4 which shows the loss of life in percentage of the loss of life

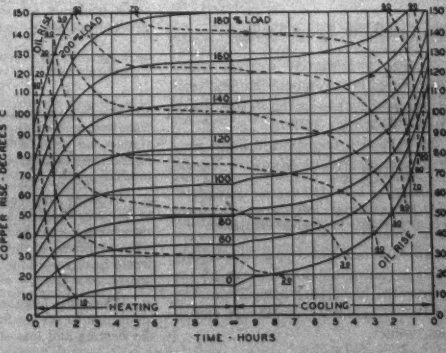

Figure 5. Heating and cooling curves for a typical transformer for various loads for the following full-load values:

Hot-spot gradient of 30 degrees centigrade, oil rise, 35 degrees centigrade, ratio of copper loss to iron loss, two, thermal time constant, two hours. Rises shown are hot-spot copper and top oil rise above ambient-air temperature

of a transformer operated continuously with a hot-spot copper temperature of 95 degrees centigrade. For convenience in calculation it may be assumed that the ultimate temperature is maintained for the total time the load remains constant. (If more precise values are desired, the curve of temperature versus time may be drawn.) The comparative loss of life may be determined as shown below. The average rate of loss of life over the period considered is the rate of aging relative to the base rate of continuous operation at 95 degrees centigrade hot-spot temperature.

EXAMPLE

What is the loss of life during the preceding example as compared to the loss of life at 95 degrees centigrade when the following temperatures were obtained:

68 degrees centigrade at end of two hours of 100 per cent load
92 degrees centigrade at end of one hour of 140 per cent load
68 degrees centigrade at end of one hour of 80 per cent load

What is the highest ambient temperature at which this loading could be carried without the average rate exceeding the normal rate of loss of life?

From Figure 4, the rate of loss of life at 68 degrees centigrade is 0.10; and at 92 degrees centigrade, 0.74 times the rate of loss at 95 degrees centigrade.

$$\text{The average rate} = \frac{0.10\times 2+0.74\times 1+0.10\times 1}{4} = 0.26 \text{ times the}$$

rate of loss of life at 95 degrees centigrade

This corresponds to an equivalent temperature from Figure 4 of 79 degrees centigrade for the four-hour period. The ambient temperature was ten degrees centigrade; it could have been 95 degrees centigrade − 79 degrees centigrade = 16 degrees higher or equal to 26 degrees centigrade before the average rate of loss of life exceeded the normal rate.

Safe Loads for Short Times

Another approximate method which may be used is to compare the final temperatures with those given in the Standards for short-time loading.

The following temperature limits may be used for recurrent loads:

Two hours or less—110 degrees centigrade
Eight hours or less—105 degrees centigrade
24 hours or less—95 degrees centigrade

Transformer hot-spot copper temperature which is calculated as the sum of the temperature rise from Figure 3, and the ambient temperature should not exceed these values.

If the temperatures obtained during the desired loading do not exceed these values for the times corresponding to the temperature rises on the curve of Figure 3, the loading will be within safe limits. In the preceding example, the copper temperatures given in Table II were obtained with ten degrees centigrade ambient: The temperature limit for 4.8, 3.2, and 7.6 hours is 105 degrees centigrade as shown in the last column of Table II. The final copper temperatures are all below the limit, so consequently the loads may be carried with safety. According to Table II, the ambient temperature could have been equal to 105 − 92 = 13 degrees higher or equal to 23 degrees before safe temperatures were exceeded. This approximate value may be compared with the more accurate value of 26 degrees centigrade obtained by the previous method.

Summation

The general principles underlying safe loading of transformers can be conveniently expressed on a quantitative basis by the use of charts. These charts consider the effect of ambient temperature and thermal capacity of the transformer as well as the other physical constants of the transformer. Thermal characteristics of a transformer cannot be precisely determined, but fortunately precise determination is not necessary for practical use. By using assumed values for constants which give results on the safe side (for example, using a gradient for calculation which is not smaller than the actual gradient, using a thermal time constant which is not larger than the actual time constant) one may be certain that the loading obtained is conservative. This follows the general principles in common use for overloading transformers. The heating of other apparatus follows the same laws as the heating of transformers. Similar charts can be prepared using the same principle for the set of constants which apply to the particular apparatus.

Conclusions

1. The fundamental principles involved in transformer heating and overloading are simple and applicable not only to transformers but to other devices which generate internal heat.

2. By using simple charts, the advisability of a contemplated overload cycle for a transformer can be quickly determined. The usefulness of the American Standards would be increased by the inclusion of such charts.

3. Where the more general rules are not applicable to the loading being considered, the heating and loss of life for the loading can be quickly calculated by the method given.

4. In overloading transformers, the cautions given in the interim report should be observed.

5. If a short-time overload is to be carried on an existing transformer, the starting point in determining the safe time for the load should be the present oil temperature.

Appendix. Description of Curves

The curves of Figures 2, 3, and 5 are curves of heating and cooling versus time and are calculated curves which closely approximate the curves which would be obtained if frequent readings were taken on a transformer in operation, starting with the transformer oil at air temperature for the heating curves and starting with the oil at 100 degrees centigrade rise for the cooling curves. An extensive exposition of the existing relations is given in the references, especially references 2, 5, and 20. The curves are calculated in accordance with these references. To make the curves more generally useful, the effect of thermal capacity of the copper alone is neglected. This produces appreciable error only for short times on the order of 15 minutes or less, and even there the effect is to increase the safety of loading.

Table II

Final Time (Hours)	Final Copper Rise	Final Copper Temperature With 10 Degrees Centigrade Ambient	Temperature Limit
4.8	58	68	105
3.2	82	92	105
7.6	58	68	105

The curves are drawn for the following relations of references 2, 5, and 20:

1. The ultimate hot oil rise over ambient air varies as the 0.8 power of the loss. Consequently the heat dissipation from the oil to the air varies as the 1.25 power of the temperature.

2. The copper loss varies as the square of the load.

3. The hot-spot copper gradient varies as the 1.6 power of the load.

4. The thermal time constant of the copper alone is assumed to be negligible.

5. The thermal time constant of the whole transformer is assumed to be constant at the given value.

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5. EFFECT OF OVERLOADS ON TRANSFORMER LIFE,

The Vibration of Electric Contacts

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IN evaluating an electric switching device, its following characteristics must be considered:

1. Ability to close the circuit without undue deterioration of contacting points.
2. Ability to carry the current without injurious temperature rise.
3. Ability to interrupt the circuit with the least destruction of contacting members.

Considerable attention has been given to the study of the two latter problems, while the "making" of contacts has been practically neglected. However, the engineers interested in the life or in the proper operation of switching devices realize that, in many applications, particularly those involving high initial power surges, the "making" of the contacts may be even more important than their "breaking" performance.

A switch, to "make" properly, must bring the contact points into union without their bouncing or vibrating. That is, once touched, the points should not separate, for otherwise the circuit would be momentarily broken with resulting arcing.

Particularly vulnerable are the contacts controlling tungsten filament lamps. In such circuits, because of the high temperature coefficient of resistivity of the filament material, the initial current is several times that of the normal lamp current. A typical oscillogram, Figure 1, recorded an inrush current of 800 per cent of the normal. Consequently, if vibration of contacts occurs, during their "making" period, the contact points are called upon to interrupt and to "close" a load eight times their rated capacity. Such excessive current, of course, destroys the contacting parts very rapidly.

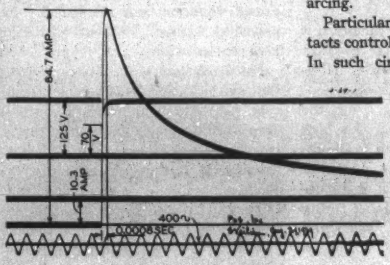

Figure 1. Oscillogram showing current rise in 1,200-watt lamp circuit on 125 volts, direct current

Vibrating contacts impose a greater duty on the contacting members. Such contacts are subjected to the load interruption, not only during their "breaking" function, but also while they are "making." Naturally, in circuits producing high current surges, this condition causes very rapid disintegration of contact material and welding. The results of vibrating contacts controlling a circuit of lamps are shown in Figure 2. Specimens 2a were closing and opening a circuit having lamps as load and are showing severe pitting and wear of metal at the center portion of the contact; it was caused by "breaking" the circuit after initial "make." Specimens 2b were controlling a d-c noninductive resistance load and are characterized by deterioration of metal at the wings of the contact; this wear was caused by arcing incident to "breaking" of circuit; it will be observed further that the center portion of the contact was not affected because of absence of high current surges in noninductive resistance circuit. Life of contacts vibrating during "making" is reduced, and, in some circuits, their use becomes prohibitive.

Similar destructive results occur in switches controlling motors, since the starting current of motors is several times their "running" values.

In the application of contacts involving sending out a predetermined number of impulses (telephony, electric clock systems, supervisory control, and so forth) for selection of indication or of a function of remotely located apparatus, the contacts must be vibrationless, for otherwise

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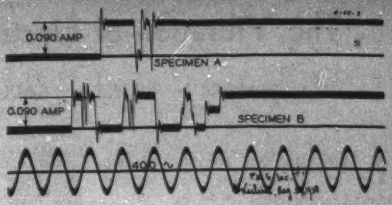
(a). Switch contacts controlling lamp load circuit

(b). Switch contacts controlling noninductive resistance circuit

Figure 2

Figure 3. Oscillogram showing contact vibration of ordinary snap switch

Snap switches closing noninductive resistance circuit on 125 volts, direct current



the number of "makes" and "breaks" would not correspond to the assigned code, thus producing erroneous results. While the effect of vibrating contacts may be compensated by the use of slow-acting magnets, such a scheme is not desirable, for it limits the speed of the system.

Functionally the contacts may be divided into two general groups: butting type (contactors, relays, switches, keys, circuit breakers, and so forth) and knife type (knife switches, snap switches, oil switches, circuit breakers, and so forth).

In a switch of elementary design, the blades may produce violent vibration, as indicated in oscillogram Figure 3. Observe several complete circuit interruptions by either specimen. Butting type of contacts, such as used in relays, keys, and so forth, usually close with pronounced bouncing, as shown in Figure 4. Many circuit interruptions took place in relatively lengthy periods of time elapsing between first "make" and final completion of the circuit, in both exposures. Therefore, the matter of vibration suppression becomes an important problem in switching mechanism designs.

For vibrationless operation, it is necessary to prevent contact overtravel at right angles to the direction of movement in case of the knife type of contacts, and to eliminate bouncing in case of butting type. In either case the energy of the moving system in excess of that utilized to unite contacts must be dissipated. Unless this is done, the impact will cause rebound.

For the interruption of d-c circuits, it is generally considered that the contacts must travel with high velocity. However, such a characteristic is objectionable during their "making," for the kinetic energy resulting from this high velocity would be more difficult to absorb.

One of the most common means of contact vibration suppression is to design the stationary contact under spring pressure, so arranged that, when the moving contact strikes the stationary contact, the spring absorbs the energy of the moving system.[1] Similar results may be obtained by the use of a dashpot, which would be put into action on the closing of contacts and thus would act as a a damper in absorbing the energy of the movable contact.

Another method of reducing the contact vibration is to use hollow contacting points,[2] filled with metallic powder. When suddenly arrested by the stationary contact, the powder particles create heat because of friction between them, thus dissipating the energy which would have produced vibration.

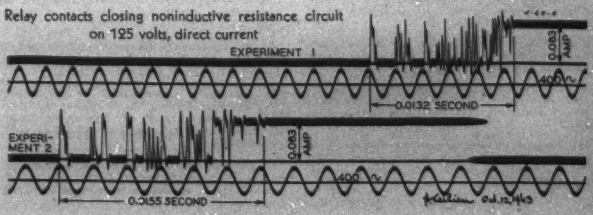
The snap switch offered a particularly difficult problem. Because of its limited size and low cost, elaborate means for the absorption of energy could not be incorporated. Consequently, it was necessary to devise some arrangement to suppress the vibration without external means. The investigation resulted in a contact with self-contained vibration suppressor. This was accomplished by preloading mutually two halves of the flexing contact member. Thus, when the flexing contact arm engaged the stationary member (like a knife switch) the energy, which would have caused vibration, was absorbed by the preloaded contact, without sacrificing high contact velocity.

For the analysis of the factors affecting the "making" of contacts, assume a knife-type snap switch, in which a movable flexing blade engages stationary contacts, completing the circuit. It will be apparent from further discussion that the analysis is applicable to any type of knife contacts. In this switch the movable element (the blade) is brought into rapid motion by a spring which is suddenly released, having been gradually loaded previously by the movement of a manually operable handle. Thus, the operator has no control of the speed with which the contacts engage. The blade collides with the stationary contacts during "making," and this action can be treated as an impact.

Experimental investigations of contact vibration required the study of several pertinent factors. Actual oscillograms, mentioned heretofore, give indications that the oscillations are damped, as expected; the velocity of the moving system is high;[3] the mass of the moving system cannot be materially reduced without the detrimental effects of high current density of current-carrying parts,

Figure 4. Oscillogram showing circuit interruptions during "making" of relay contacts

Relay contacts closing noninductive resistance circuit on 125 volts, direct current



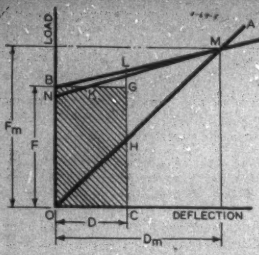


Figure 5. Graphical representation of characteristics of preloaded contact springs

or without making the mechanism undesirably small.

Analysis indicates that there is oblique impact between the blade and the stationary contact which tends to cause a rebound at an angle. It seems quite clear that, without the application of some

Figure 6. Right switch blade contact after 60,000 closures of circuit containing lamps. Left blade unused

external force, the blade after impact will separate from the contact, if the blade is a free acting spring. Rebound may be prevented by preloading the blade to the extent necessary to reduce to zero the component of the blade energy perpendicular to its travel.

In Figure 5:

D = blade travel after impact within which rebound energy is to be absorbed

F = average force which, acting through distance D, is equivalent to the kinetic energy component perpendicular to the blade travel

D_m = maximum blade deflection

F_m = maximum blade pressure

The work represented by the area $OBGC$ is equal to the kinetic energy of the component of rebound perpendicular

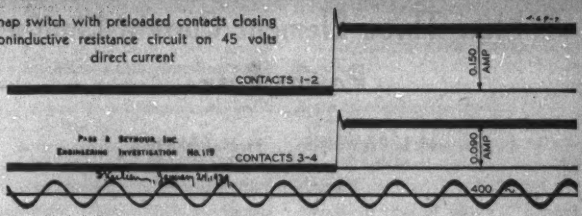


Figure 7. Oscillogram showing vibrationless contact closures of preloaded blade contacts

to the blade travel. This is the amount which must be balanced by the work of deflecting the blade.

The load deflection curve OA represents a spring blade of suitable characteristics to give adequate contact pressure F_m at maximum deflection D_m, but it is seen that the area, OHC, representing the work done in deflecting the spring distance D, is less than $OBGC$ and, therefore, insufficient to prevent rebound.

The spring blade, however, which will just prevent rebound, will have a load deflection curve NM with ON representing the preload. Or a spring having the loading characteristic BE will provide a factor of safety.

To check the results experimentally, a number of switches built with the blades of suitable design were tested under most severe practical load (tungsten filament lamps with a special generator capable of producing the high surges needed.)[4] The test specimens were arranged so that the contacts were only "making" under load, while the "breaking" of the circuit was accomplished by another device. There was no visible pitting on any specimen, indicating vibrationless "make," even after 60,000 operations. The appearance of a specimen after test is given in Figure 6, in which the right-hand contact discloses slight grooves resulting from mechanical abrasion of parts. The left-hand blade is an unused sample and is shown for comparison.

Oscillograms further substantiated vibrationless contact (see Figure 7), for the circuit controlled by the contact was not broken after the initial "make." The slight saw-tooth shaped lines at the start of "on" period and at the end of "off" period, as shown on this and previously mentioned oscillograms, represent the record of the galvanometer overtravel, and should not be interpreted as circuit interruptions.

In actual practice the contact is called upon not only to "make" but also to "break" the lamp load circuit. Injuries to contact surfaces resulting from "breaking" contribute to their imperfect "making," ultimately destroying the contacts in spite of the designs, exposing different areas of the contact during "making" and "breaking." The life of switches having preloaded blades has been increased several times as compared with that of a conventional design having no vibration suppression means. This fact has been substantiated by tests of a large number of specimens.

It is quite apparent that designing the contacts so that the energy causing vibration is absorbed at the instant of impact may be readily accomplished by the mutual preloading of the contact blades. Under such conditions the vibration may be eliminated completely, producing a marked increase in the longevity of electric contact.

There is a tendency to increase the load controlled by switch contacts, particularly in the field of lighting. This condition has been created by higher levels of illumination and the impracticability of increasing the number of conductors in existing wiring. Short life may be expected in such cases with switches whose contacts are not suitably designed. Wider application of various contactors, relays, industrial switches, and more stringent requirements in their performance emphasize the necessity of having vibrationless contacts. The described method of vibration suppression, because of its simplicity, could be applied successfully to many switching devices whose vibrationless contact operation is paramount for reliable performance.

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A New Three-Element Current-Limiting Power Fuse

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Synopsis: In order to meet the requirements for the protection of high-voltage motor starters and for protecting small loads and apparatus connected to those parts of electric systems having extremely high short-circuit currents, it has been necessary to increase the current range of the three-element current-limiting fuse. This fuse, which was announced in 1940, has been in commercial use for over two years in the lower ampere ratings.

The development of higher current ratings in a fuse of suitable dimensions produced problems and solutions totally different from those previously encountered. A new type of fusible element has a time–current characteristic particularly suited to current-limiting fuses. Extremely fast melting times on high currents to give correct current-limiting action are combined with a continuous current-carrying capacity and normal melting time of an element having five times the area previously associated with the current-limiting characteristic. The association of this element, with gas-evolving material and quartz sand to give quick and positive current limitation while the metal vapors are absorbed, results in an entirely new fuse construction. The combination of this current-limiting element with a noninductive resistor of special characteristics and a totally enclosed boric-acid "clean-up" fuse has resulted in a current-limiting fuse of more compact construction than has been available heretofore in the ratings involved. Exhaustive tests have demonstrated the suitability of the new fuse for application on high-capacity systems to interrupt the full range of fault currents with minimum system disturbance.

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IN order to meet the requirements for a fuse of small size with current-limiting characteristics for connecting light loads and small apparatus to high power systems, a new form of current-limiting fuse was developed and announced in 1940. Three distinct elements characterized this fuse.

1. A current-limiting fusible element which produced a high arc voltage to limit the current.
2. A resistor in parallel with the fusible element to limit the voltage to a predetermined value.
3. A series fuse to interrupt the power follows current through the resistor.

The fuse proved capable of interrupting the highest currents, up to 130,000 amperes at 13,200 volts, without producing voltages in excess of 150 per cent of the peak circuit voltage.

The excellent service record of fuses built with this principle and the inherently higher interrupting ability of current-limiting fuses, coupled with the necessity for limiting the fault current in motor starters and similar apparatus, make it desirable to extend the current range of the current-limiting fuse announced in 1940. In considering the desirable limits in current ratings for current-limiting fuses, the following factors must be considered:

1. The effect of current rating on the current-limiting characteristic. As the current rating of a current-limiting fuse increases, the current to which a fault can be limited also increases, thereby nullifying the beneficial effects of a current-limiting fuse. By reference to Figure 1 it can be seen that the current-limiting effect of a fuse rated above 200 amperes would be appreciable only on systems having high values of short-circuit current.

2. Current-limiting fuses for motor starters are required to have high current ratings with moderate interrupting capacity, whereas current-limiting fuses for station auxiliaries and similar services are required to have high interrupting capacity and relatively low current ratings. The heavier current distribution service can be fulfilled more economically by fuses of lower interrupting rating.

From a consideration of these factors it would seem desirable to extend the new current-limiting fuse to cover a continuous current rating of 200 amperes for voltages through five kilovolts for motor-starter applications, and to cover continuous current ratings of 100 amperes for voltages above five kilovolts to permit tapping small loads from high-capacity systems. Edison Electric Institute and National Electrical Manufacturer's Association have adopted recently the "E" rating for power fuses, which specifies that fuses will carry 100 per cent of rating continuously and melt in exactly five minutes at 200 to 240 per cent of the rating for fuses 100 amperes and below and in exactly ten minutes at 220 to 264 per cent of rating for fuses above 100 amperes. It is seen readily that, for "E"-rated fuses, the proposed ratings cover a wide field of application.

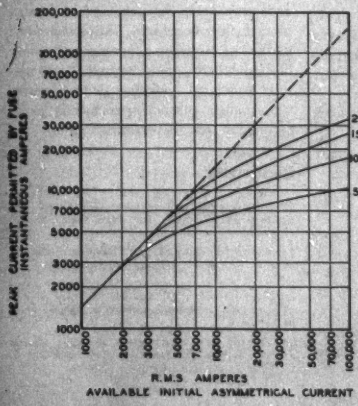


Figure 1 (left). Current-limiting characteristic curves showing maximum peak current permitted by new three-element power fuse for all values of available short-circuit current

Figure 2. Construction of 2.5-kv 200-ampere three-element current-limiting fuse

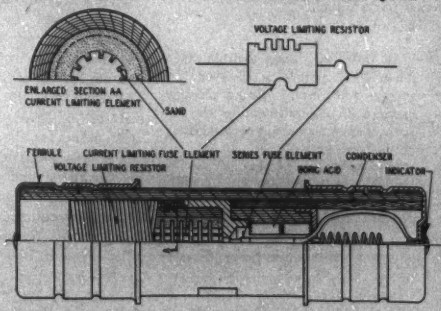


Figure 3. Five-kilovolt 200-ampere fuse unit in disconnecting-type mounting

In extending the current range of the fuse embodying the new current-limiting principles, it was recognized soon that the same materials and construction as used in the lower ampere ratings could not be used without resulting in a fuse of prohibitive size and cost. The 200-ampere rating could not be obtained in a single fuse of reasonable proportions with proper current-limiting characteristics simply by increasing the number of parallel silver wires in the current-limiting element.

The parallel resistor which diverts current from the current-limiting element required radically different characteristics in order to handle the higher currents in a device of reasonable dimensions. The absorption of metal vapors from a new type of heavier fuse element required a novel construction.

The development of higher current ratings, therefore, produced problems and solutions completely different from those in the lower current ratings.

Construction of the New Fuse

The electrical and physical relationship of the three basic elements in the new fuse are shown in Figure 2, while the overall appearance of a complete fuse with disconnect mounting is shown in Figure 3. As in the current-limiting fuse for lower current ratings announced in 1940, the new power fuse comprises a current-limiting element shunted by a resistance or voltage-limiting element with a series "clean-up" element. All three of these elements are contained in a simple nonrenewable cartridge that is much smaller than existing indoor-type power fuses of lower interrupting capacity and smaller-than-conventional current-limiting fuses of equal rating. The outer casing of heavy Micarta tube with spun-on ferrules contains in one end the assembly, consisting of the current-limiting element and shunt resistor; immediately adjacent is the series-calibrated fuse element in its boric-acid-lined chamber, which on interruption exhausts into the condenser in the other end of the casing.

The heart of the new power fuse is the current-limiting element which is contained in a high-strength fibre tube with threaded ferrules. The conducting portion of the current-limiting element consists of a plurality of specially rolled silver wires supported in a slotted fibre bar. As shown in Figure 4, each silver wire has the appearance of a string of sausages. This construction is obtained by rolling a large diameter wire with reduced sections of approximately one sixth the cross section of the main wire. The restrictions are spaced equally at intervals throughout the length of the conductor. The grooves in the fibre support are approximately twice as deep and slightly wider than the diameter of the silver conductor. The conductor wires are placed in the bottom of the grooves in intimate contact with the fibre, except on the open side of the groove. Fibre washers equally spaced on the slotted fibre bar retain the conductors in the grooves. The space between the fibre support and the fibre casing is filled with a coarse quartz sand of uniform size.

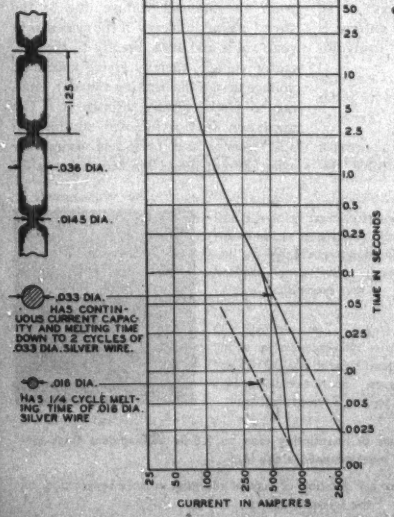


Figure 4 (left). Enlarged view with melting-time-current curve of individual current-limiting fuse element

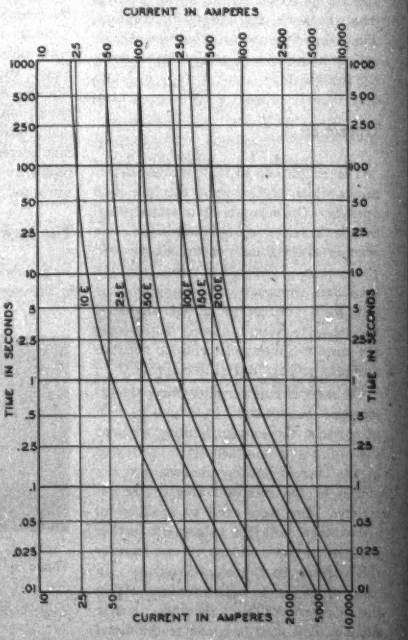


Figure 5 (right). Minimum-melting-time-current characteristics of representative current ratings of three-element power fuse

The shunt resistor or voltage-limiting element which eliminates high-surge voltages incident to current limitation is connected permanently in parallel with the current-limiting element. The resistor consists of two insulated resistance wires wound directly onto the fibre shell of the limiter element and connected on each end to the limiter ferrules. The two layers of resistance wire are wound in opposite directions to minimize inductance. The special resistance wire is essentially nonmagnetic, possesses the virtue of having a moderate positive temperature coefficient of resistance, and has the proper specific resistance for the resistances and sizes needed.

The melting time–current characteristics of the fuse, as shown in Figure 5, are determined by the calibrated element in the boric-acid series fuse. This element is a low-temperature type which consists of a heater and fusible alloy for long melting time characteristics and a reduced fusible section for short melting time characteristics. The series-fuse member is spring withdrawn through the boric-acid-lined interrupting chamber into the condenser to insure fast clearing of low current faults. The condenser consists of several layers of coarse-mesh copper screen which presents the maximum surface to condense the steam evolved from the boric acid during interruption. The action of the operating spring mechanically releases an indicating target outside the ferrule.

Operation

The magnitude of fault current determines which of two ways the fuse shall operate. On currents of overload magnitude the series fuse operates in the same manner as the totally enclosed boric-acid power fuse. The blast of steam from the boric acid deionizes and extinguishes the arc, while the copper screen condenses the steam to water. During this process the current-limiting elements do not fuse and play no part in the interruption.

On short-circuit currents where the series fuse element melts in a small fraction of a cycle, the current-limiting element melts almost simultaneously. The fusion of the current-limiting element and the action of the resultant arcs in the restricted fibre slots tend to produce an arc voltage sufficient to prevent further increase in the fault current and transfer the current to the shunt resistor. In order to eliminate high pressures within the current-limiting chamber, coarse silica sand is used to condense the metal vapors from the fusible elements and cool the fibre gases.

The resistor in parallel with the current-limiting element, being noninductively wound, will stabilize the voltage that occurs during interruption. The maximum voltage that can appeal is simply the *IR* (current-resistance) drop through the resistor. When the instantaneous peak current permitted by the current-limiting element, which can be determined from the curve shown in Figure 1, is known, a value of resistance may be chosen to limit the voltage to any desired figure. It has been determined by repeated tests, however, that all of the current does not transfer instantaneously to the resistor. On high current interruptions approximately 25 per cent of the peak current will continue to flow through the current-limiting element for a short time, resulting in a peak voltage 25 per cent less than the calculated value. In addition to controlling the voltage surges during interruption, the resistor very materially reduces the duty on the current-limiting element. The total energy absorbed by the current-limiting element is less than 15 per cent of the energy that it would absorb without the parallel resistor. This makes possible a very compact current-limiting assembly and is a material factor in the small over-all size of the complete fuse.

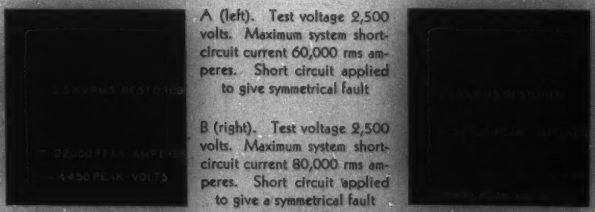
On the high values of short-circuit currents where the series-fuse element melts almost simultaneously with the current-limiting elements, the series fuse arcs throughout the current-limiting action and interrupts the resistor current at the first current zero. Since this current is resistance limited, it is very easily interrupted.

The New Fusible Element

Of particular interest and importance is the new current-limiting fusible element. Although various shapes and sizes of fusible elements have been used to obtain different desired characteristics, there have never been any designs to obtain the peculiar characteristics desired in a current-limiting fuse. The element shown in Figure 4 has all the normal characteristics desired in a fuse for time values in excess of approximately two cycles, and yet for short times of less than one-quarter cycle, it has a very fast melting time. This shift in characteristics results in a fuse that limits the current to 38 per cent of the value that would be obtained if simple straight wires were used. The use of these fusible elements makes possible the cool operation of the high current ratings when carrying full-rated current.

Summary of Tests

The thorough testing of current-limiting fuses involves testing under all degrees of asymmetry as well as on high and low fault currents with various circuit constants, since the severity of duty on the various components of the new current-limiting fuse varies with the point on the generated voltage wave that the current-limiting fuse element melts. A synchronous short-circuiting switch may be used conveniently to obtain these various degrees of asymmetry. The maximum duty on the current-limiting element and the maximum voltage surge due to current limitation occur when fusion of the current-limiting element occurs at normal voltage peak, since at this point the induced voltage due to the stored magnetic energy of the system is at peak value and adds directly to the generator voltage, thereby giving maximum voltage across the limiting element, tending to force current through it. The maximum duty is imposed on the parallel resistor and boric-acid series fuse when current limitation occurs just after



A (left). Test voltage 2,500 volts. Maximum system short-circuit current 60,000 rms amperes. Short circuit applied to give symmetrical fault

B (right). Test voltage 2,500 volts. Maximum system short-circuit current 80,000 rms amperes. Short circuit applied to give a symmetrical fault

Figure 6. Magnetic oscillograms of interrupting tests on 2.5-kv 200-ampere three-element current-limiting fuse

Note higher peak voltage and longer duration of current resulting in more severe duty on the asymmetrical test

Figure 7. Cathode-ray oscillogram of voltage during interruption by 2.5-kv 200-ampere fuse shown on magnetic oscillogram, Figure 6B

voltage zero, and these two elements carry current until the next voltage zero.

Consider the case of a high-ampere-capacity fuse where an appreciable time is required for melting the current-limiting element. If the fault is initiated at zero voltage, the system voltage will be approaching normal peak value when fusion occurs. Since this condition imposes the most severe duty on the limiter, it follows that an asymmetrical fault represents the most difficult problem of interruption for high-ampere-capacity fuses. On low-current fuses, where fusion of the current-limiting element occurs in a very short time interval, a fault initiated just prior to normal voltage peak or a symmetrical short circuit represents the most severe duty. Therefore, the degree of asymmetry required for the most difficult operation is a variable depending on the current rating of the fuse and the magnitude of the available short-circuit current.

Consequently, all ratings of fuses have been tested at rated voltage with all conditions of asymmetry on currents of varying magnitudes from minimum melting current up to the interrupting rating of the fuse. Representative magnetic and cathode-ray oscillograms are shown in Figures 6 to 8. The magnetic oscillograms clearly show when current ceases to flow in the current-limiting element, as indicated by the voltage trace changing from a high arc voltage to the smooth sinusoidal form of the generator voltage, and the current trace simultaneously changing from a rapid decline to a sinusoidal form modified by the increasing resistance of the shunt-voltage-limiting element. The cathode-ray oscillograms show that the surge voltage accompanying current limitation does not exceed 160 per cent of normal system voltage on the highest asymmetrical fault currents with high-current fuses. This combination represents the condition under which maximum voltage will be obtained. With any other degree of asymmetry or lower fault current the voltage surge will be less.

A comparison of the magnetic and cathode-ray oscillograms shows that a quick response magnetic oscillograph is entirely adequate for measuring the voltage phenomena of this fuse.

The design of current-limiting fusible elements combined with the low-temperature-type series fuse makes possible the highest desirable current rating in a single fuse unit. On temperature rise tests the 200-ampere fuse carries full rated current without exceeding 30 degrees centigrade rise on the ferrules above a 40-degree-centigrade ambient temperature.

In addition to interrupting tests on the fuse units alone, numerous combination tests have been made with new motor starters throughout the entire current range from overload currents, which the starter interrupts without melting the fuse, to the highest values of short-circuit current, for which the fuse is designed, in which case the fuse interrupts the fault with no damage to the starter. A starter for such combination service must be designed for the particular duties involved.

A

B

A. Five-kilovolt 200-ampere fuse. Test voltage 5,000 volts, available short-circuit current 60,000 rms amperes

B. 15-kilovolt 25-ampere fuse. Test voltage 13,800 volts, available short-circuit current 90,000 rms amperes

Figure 8. Magnetic oscillograms of interruptions

Short circuit applied to give asymmetrical fault

Conclusions

The current ratings of the three-element current-limiting fuse have been extended by the adoption of new features. Of particular importance is the current-limiting fusible element that gives a time-current characteristic particularly suited for current-limiting fuses. The new features combined in a compact structure permit current ratings ample to protect high-voltage motor starters, other types of apparatus, and small loads connected to high power systems. The new power fuse has the desirable qualities of the lower-current three-element current-limiting fuses in that the voltages during interruption are controlled definitely to eliminate harmful overvoltages.

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Thermal Protection of Transformers Under Overload Conditions

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Synopsis: The overloads recommended in the AIEE transformer subcommittee's report,[1] "Emergency Operation of Transformers," are based on considerably higher transformer hot-spot temperatures for short-time operation than those given in and used to derive the emergency overloads recommended in the American Standard Guides for Operation of Transformers and Regulators C-57.3.

Overloads may be obtained in close agreement with the recommended emergency overload curves by the use of a relay which is controlled by a specially designed heating coil or by a specially designed relay with a conventional heating coil. Since a relay operates at about the same temperature irrespective of time to avoid too high hot-spot temperature for ultimate conditions, the relay and heating coil must have such characteristics as to permit the transformer hot-spot temperature to reach considerably higher values for short times than for ultimate steady-state conditions. A detailed study of this problem has shown that this may be accomplished satisfactorily by the use of a lagged heating coil which has a relatively large time constant in comparison with that of the transformer winding or by the use of a heating coil, the time constant of which is about the same as that of the winding for operating a relay that is compensated for the changes in ambient temperature.

This relay which has been developed can be set to perform three separate functions: control fans, give a warning signal, and sound an alarm or, if desired, trip the transformer off the circuit. A diagrammatic sketch and photographic prints show the various combinations of bulbs and relays available. It is believed that the relay allows the transformer to be loaded more nearly in agreement with the recommended industry loadings than any previous available device.

THE AIEE transformer subcommittee[1] has recommended higher overloads than those given in the ASA Guides for operation of transformers. These overloads are set up on the assumption that, under rare emergency conditions, it is better to use up a small amount of the expected life of the transformer than to have an interruption of service. Therefore, as a result of the work of the AIEE and the ASA, a demand is developing for a relay that will close its contacts when the limiting load condition is reached.

Since these emergency overloads are based on hot-spot temperatures, the most direct way of safely utilizing the extra capacity would be to furnish a relay with the proper time–temperature characteristics and to operate it from a standard artificial hot-spot heater element. While it may be possible to design such a relay, it does not appear practical, because a relay is normally sensitive to temperature but not to time when it is longer than several minutes; consequently, other means are suggested as follows:

1. To operate a fixed temperature relay from a lagged heating coil (immersed in the cooling fluid),* the time constant of which is many times that of the transformer winding, so that the relay does not reach its operating temperature until the winding temperature and load have risen to the desired value.
2. To operate a relay having an ambient-temperature correction from a heating coil, the time constant of which is the same as that of the transformer winding.

An extensive investigation has shown that, in order to obtain satisfactory results under all conditions, a part or all of the following factors should be taken into consideration:

1. Transformer characteristics—hot-spot rise, top oil rise, oil time constant, and ratio of losses.
2. Time constant of the heating coil immersed in the oil.
3. Temperature rise of heating coil over oil at rated load.
4. Relay operating temperature.
5. Effect of ambient temperature on relay operating temperature.

The purpose of this paper is to show what has been done in meeting the recommended emergency overload curves by taking into account the previously mentioned factors. Finally, calculated overloads obtained with thermal protection on transformers with average characteristics are compared with the rare emergency overloads recommended in the AIEE interim report[1] and the usual emergency overloads recommended in the ASA Guides for operation of transformers, C-57.3.

* The cooling fluid may be mineral oil or any of the noninflammable synthetic liquids (Askarels) developed for transformer use.

Design of Heating Coil to Meet the Overload Requirements

The use of an ordinary hot-spot indicator and a standard thermostat for overload protection is impractical, because the thermostat, operating relatively quickly at a fixed temperature, could not distinguish between long and short-time intervals and, hence, would operate too quickly in the short-time range, or vice versa.

It is well known that the oil of a transformer has a time lag of several hours due to the total heat-storage capacity of the transformer, whereas, the time lag of winding rise over oil is in the order of 15 to 20 minutes. This means that a relay operated by oil temperature alone would permit excessive winding temperatures under short-time heavy overload conditions, particularly in low ambient temperatures. The scheme of using a thermal relay (immersed in the transformer oil), the temperature rise of which is responsive to load current, has been described[2] and has been in use for several years for thermal protection of transformers.

To obtain satisfactory results with a scheme employing a relay responsive to load current, the temperature rise of the relay (or of a heating coil controlling the relay) must be less than the hot-spot rise over top oil at rated load. Furthermore, the relay must be set to close its contacts at some temperature above that resulting from 100 per cent ultimate conditions in a 30-degree-centigrade ambient temperature. Then on overloads, by the time the temperature of the relay has reached its tripping point, the hot-spot rise will have attained higher values for the higher overloads. It is this difference in the rate of temperature rise that allows the higher hot-spot temperatures for the short-time overloads.

However, if the ambient temperature changes, this scheme does not give correct results in that, if set to allow correct short-time loading at the higher ambient temperatures, it allows too high loadings at the lower ambient temperatures. This deficiency can be corrected by introducing an ambient-temperature

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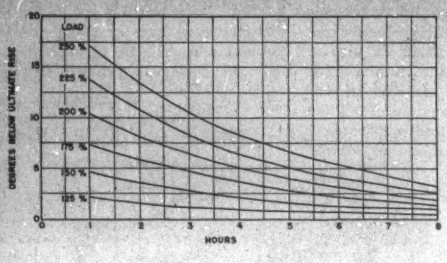

Figure 1. Depression (degrees below ultimate rise) curves for lagged heating coil immersed in oil of transformer under overload conditions following full load

Transformer-oil time constant = 4.0 hours

correction in the mechanism of a relay (mounted on the outside of the transformer), the contacts of which are operated by a bulb enclosed in a heating coil immersed in the top oil and responsive to the load current. On the other hand, if the heating coil is suitably designed and lagged, the ambient-temperature correction can be omitted. By choosing the proper temperature rise of the heating coil (either the lagged or unlagged) and by selecting the right tripping temperature of the relay, a wide flexibility is secured, thereby enabling one to design a protective system to function correctly for almost any condition of loading.

In connection with the use of a lagged heating coil, as long as it was only necessary to meet the ASA emergency overloads, a small amount of lagging was sufficient. However, when the AIEE transformer subcommittee set up the rare emergency overloads based on considerably higher short-time hot-spot temperatures than used in setting up the ASA emergency overloads, it became necessary to modify the design and characteristics of the thermal relay and increase the lagging effect to meet the new conditions. The time constant of the lagged heating coil is now much more than that of the transformer winding.

Table I. Comparison of AIEE and ASA Recommended Overloads With Overloads Permitted by the Protective System

		AIEE Emergency (Times Rated Load)		ASA Emergency (Times Rated Load)	
	Hours	By Relay	Recommended by AIEE*	By Relay	Recommended by ASA
Self-Cooled					
Following full-load 30-degree ambient temperature	24	1.37	1.25	1.15	1.1
	8	1.41	1.35	1.17	1.15
	4	1.52	1.5	1.22	1.2
	2	1.7	1.7	1.30	1.3
	1	1.9	1.9	1.4	1.4
Following full-load zero-degree ambient temperature	24	1.62	1.55	1.42	1.4
	8	1.69	1.65	1.47	1.45
	4	1.84	1.8	1.57	1.5
	2	2.1	2.0	1.75	1.6
	1		2.0	2.0	1.7
Following no-load 30-degree ambient temperature	24	1.37	1.25	1.15	1.10
	8	1.47	1.45	1.3	1.25
	4	1.71	1.7	1.42	1.35
	2	2.05	2.0	1.7	1.50
	1		2.0	2.1	1.60
Following no-load zero-degree ambient temperature	24	1.62	1.55	1.42	1.4
	8	1.75	1.75	1.55	1.55
	4	2.0	2.0	1.75	1.65
	2		2.0	2.15	1.8
	1		2.0	2.6	1.9
Forced-Air-Cooled					
Following full-load 30-degree ambient temperature	24	1.7	1.53	1.52	1.46
	8	1.72	1.66	1.55	1.53
	4	1.8	1.8	1.6	1.6
	2	1.94	1.93	1.73	1.73
	1	2.13	2.13	1.88	1.86
Following full-load zero-degree ambient temperature	24	1.94	1.755	1.8	1.685
	8	1.97	1.885	1.82	1.755
	4	2.07	2.025	1.9	1.825
	2	2.27	2.155	2.1	1.95
	1	2.50	2.355	2.3	2.085

* The maximum load recommended is two times rated load. For forced-air-cooled rating the maximum load recommended is 2.66 times the self-cooled rating.

The problem of calculating the temperature rise of the heating coil (over top oil) to obtain the right time constant under the new condition was found to be very complicated. Tests have shown that, for a transformer winding or a heating coil with no special lagging, the ultimate rise is reached in approximately the same time (15 to 20 minutes), whether the oil temperature is constant or is increasing. However, when a heating coil is lagged, so that it reaches ultimate rise in a given time in oil at a constant temperature, it requires a much longer time to reach its ultimate rise when immersed in oil, the temperature of which is increasing. Theoretically, its rise does not become constant so long as the temperature of the oil is increasing, but it becomes practically constant in eight to ten hours, as illustrated by the "depression curves" (degrees centigrade below ultimate rise), calculated by equation 2 and shown in Figure 1.

The transient temperature rise of this lagged heating coil can not be calculated by an equation of the form usually used[3] for determining the hot-spot rise of a transformer over the oil, that is

$$\theta = \theta_u\left(1 - \epsilon^{-\frac{T}{B}}\right) \qquad (1)$$

but an entirely different formula* must be used, namely

$$\theta = \theta_u - \left(\frac{FB_c}{B_o - FB_c}\right)\left(\phi_u \epsilon^{-\frac{T}{B}}\right) \qquad (2)$$

where

θ = temperature rise of heating coil over oil, degrees centigrade

θ_u = ultimate temperature rise of heating coil over oil, degrees centigrade

F = factor allowing for the effect of distributed thermal capacitance of the lagged heating coil

B_c = time constant of heating coil

B_o = time constant of transformer oil

ϕ_u = ultimate temperature of transformer oil above the starting temperature, degrees centigrade

$\epsilon = 2.718$

T = time

Many heat runs ranging in time from one to eight hours' duration were made on a 2,500-kva transformer with heating coils having different lagging, to check equation 2 and to obtain sufficient empirical data on factor F for design purposes.

The fortunate phenomenon, whereby a rising oil temperature gave the heating coil an unexpected long time lag, helped to make it possible to design a thermal protective scheme to meet the wide variety of requirements. In order to take

* See appendix for derivation.

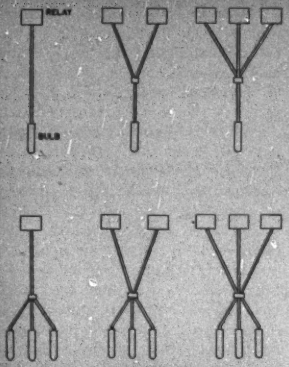

Figure 2. Six combinations of bulbs and relays available for thermal protection of transformers

full advantage of this time lag, however, the temperature rise of the heating coil over oil at rated load (since its time constant is affected by the time constant of the transformer under overload conditions) and the temperature at which it operates the relay must be selected on the basis of the individual transformer characteristics and the kinds of overloads required. Its flexibility enables one to meet almost any requirement.

Factors Affecting and Calculation of Transformer Temperature Rises

Some of the more important factors that determine short-time overloads are the oil time constant and hot-spot rise over top oil. Self-cooled oil time constants ranging from three to five hours were chosen as representative for most transformers. A survey of many recent designs for medium-size power transformers shows that the average time constant is approximately four, extreme limits being as low as three and as high as seven. For the forced-air-cooled oil-immersed ratings (1.33 times the self-cooled rating) the time constant is, of course, less, since the oil rise is much less for a given loss. Two thirds of the self-cooled oil time constant was used in calculating the forced-air-cooled loadings.

As pointed out in the paper by Montsinger and Ketchum,[3] the hot-spot rise over average winding rise in most modern transformers ranges from five to ten degrees centigrade, and for this reason it is believed that a hot-spot rise of 62 degrees centigrade (55+7) represents the average condition. This value is used later.

A formula of the general form of equation 1 should be used to calculate the oil rise before conditions become constant. Equation 2 should be used to calculate the temperature rise of a lagged heating coil over the increasing oil temperature. The temperature rise of the heating coil (at rated load) and the relay-closing temperature should be selected to give the best performance, since these must apply to and satisfy more than one operating condition.

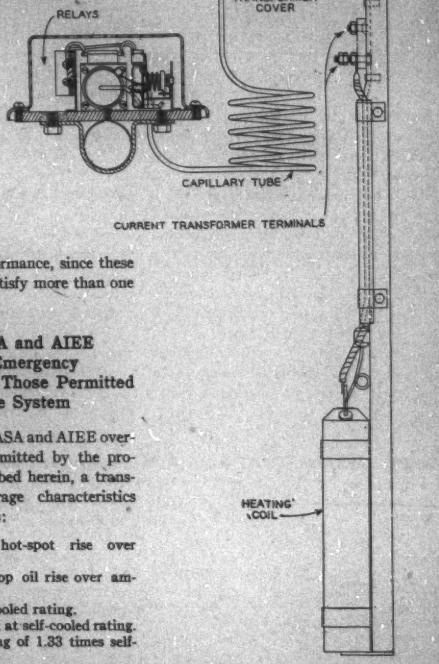

Figure 3. Heating coil and relays

Comparison of ASA and AIEE Recommended Emergency Overloads With Those Permitted by the Protective System

For comparison of ASA and AIEE overloads with those permitted by the protective system described herein, a transformer having average characteristics was chosen, as follows:

62-degree-centigrade hot-spot rise over ambient temperature.
48-degree-centigrade top oil rise over ambient temperature.
3:1 loss ratio at self-cooled rating.
4.0-hour time constant at self-cooled rating.
Forced-air-cooled rating of 1.33 times self-cooled rating.

Table I shows how well the recommended overloads can be followed with the new protective system. For the ASA emergency loads the hot-spot temperatures are below 105,* 110,* 113, 115,* and 120 degrees centigrade for 24, 8, 4, 2, and 1 hours, respectively, in 28 out of 30 conditions shown in Table I. The two cases are: 4 degrees high for 8 hours and 8 degrees high for 24 hours. Both cases follow full load in 30 degrees ambient temperature for forced-air-cooled conditions. No comparison of loads is shown for forced-air-cooled rating following no load, because this is a condition that is not very likely to occur.

For the AIEE emergency loads the hot-spot temperatures are below the recommended values for the short times but above the recommended values in all cases for 24 hours, and in some cases for 8 hours. The principal reason for this is that the temperatures are nearly enough constant in 8 hours' time to produce (with the small difference in loads permitted by the relay for 8 and 24 hours) approximately the same hot-spot temperatures as against a difference of 10 degrees centigrade in the recommended values of 120 degrees centigrade for 8 hours, 110 degrees centigrade for 24 hours. Both the 24-hour loads and hot-spot values may be reduced by insulating a heating coil sufficiently to produce a 24-hour temperature lag, but this is not ordinarily practical.

It seems reasonable to assume that, in most emergencies lasting 24 hours or more, the daily peak load would not be on more than eight hours. Furthermore, as these overloads are intended for rare emergency conditions, once a year or less often (once in 16 years, as estimated in L. W. Clark's paper),[4] the amount of aging at somewhat higher than recommended values for the full 24 hours should be acceptable.

* Recommended by American Standard C-57.3 section 11.002 (C).

Figure 4. View of bulb, capillary tube, and relays

For transformers having characteristics quite different from the aforementioned, it will be necessary, of course, to use a different tripping temperature for the relay and perhaps a different heating-coil rise at rated load.

Where the load permitted for one or two hours is above the maximum load recommended by AIEE (two times rated load), and it is desirable to limit the maximum load to this value, other means, such as overload current relays, must be arranged to come into action when the maximum desirable load is exceeded. For forced-air cooling two times rated load corresponds to 2.66 times the self-cooled rating.

In general, when the wide range of operating conditions covered is considered, the overloads line up remarkably well with the recommended values, in fact, far better than appeared possible when the problem was attacked first. If the planned conservatism of the ASA and AIEE recommendations is considered, the values given seem to be suitable for operation, but it is a simple matter to design for slightly lower loads throughout if desired.

Good results can be obtained also by using a conventional heating coil with a relay designed to close its contacts at lower temperatures in lower ambients.

Relay

In its simplest form the relay includes a bulb heated by a coil and a metallic bellows which operates a switch. The bulb and the bellows are connected through a capillary tube, and the assembly constitutes a closed system which is filled with a volatile liquid. The pressure of vaporization of the fluid is communicated to the bellows and thence to the switch.

Relay Requirements and Functions

The practical application of a relay and its heating coil to transformers having a wide variety of thermal characteristics and load cycle requirements requires certain variable features:

1. The relay contacts must be capable of being set to close over a temperature range of 90 to 130 degrees centigrade.

2. Means must be provided for selecting different temperature rises of the heating coil at rated load.

If a compromise relay setting and temperature rise of heating coil were used, some transformers would be overloaded excessively before the relay came into action, whereas, others would be loaded far below permissible values.

Figure 5. View of three relays assembled on plate of container

The new relay combination will perform three separate functions:

1. Control the fans used for supplementary cooling.

2. Give a warning signal when an overload has been on the permissible length of time.

3. Give an alarm or, if preferred, trip the transformer off the circuit when the loads exceed specified limits.

The relay can be supplied for all three of the previously mentioned functions or, if fans are not used, with only the signal and alarm circuits. The contacts are standard switches operated by vapor-tension-type bulb and bellows. The bulbs are located in the heating coil and the bellows and switches conveniently located external to the transformer.

Relay and Bulb Combinations

Six combinations of bulbs and bellows, Figure 2, are available. Figure 3 shows a sketch of the heating coil and connections to relays. Figure 4 shows bulb, capillary tube, and three relays. Figure 5 shows three relays assembled on plate of container.

The combinations shown in Figure 2 will take care of all requirements for either single-phase (with two or three windings) or three-phase transformers, that is, one bulb with one bellows will perform one function (turn on fans) on either a single-phase or three-phase unit. One bulb with three bellows will perform all three functions on a single-phase unit, or if desired it will perform the three functions on a three-phase unit satisfactorily if the load is balanced.

Three bulbs with one bellows will perform either one of the three functions on each phase of a three-phase unit or on each of three windings of a single-phase unit. Three bulbs with three bellows will perform the three functions on a three-phase unit with unbalanced loads or on a single-phase unit with three windings.

When three bulbs are used (with either one or three bellows), one in each phase of a three-phase unit or one in each of three windings of a single-phase unit, if the load is unbalanced the bellows are controlled by the temperature in the phase or winding having the greatest load. This is a new feature used for the first time with bellows, although it has been used successfully for several years in controlling three-element hot-spot temperature indicators for three-phase transformers.

These six combinations, therefore, make it possible to obtain practically ideal protection under expected load conditions.

Life Test for Accuracy and Reliability

To determine its accuracy in repeated operations one of the relays was given a life test in which approximately 6,000 operations were performed. The maximum variation was in the order of 0.5 degrees centigrade. These tests indicate that the relay has unquestionable reliability.

Means for Checking the Performance of the Relays in the Field

No matter how reliable a device is, it is sometimes desirable to make calibration tests in the field to be absolutely sure that it is in working order, and to accomplish this the relay is provided with auxiliary means to heat the relay under conditions simulating actual operative temperatures.

Application of Relay to Transformers

Several transformers have been and are now being equipped with these new heating coils and relays. The data obtained on the short-time overloads, made on a self-cooled single-phase transformer (rated H-60 cycles, 1,250 kva, 69,000 to 7,500/12,975Y volts) equipped with the new protective system, checked the previous tests made to determine the characteristics of the heating coil.

Appendix

Transient Thermal Performance of Transformer-Overload Heating Coil

The transient thermal performance of the heating coil for the transformer overload relay is quite similar to that of a transformer winding, since it is immersed in heated oil and develops an internal temperature rise over oil which must be added to the oil temperature to obtain the temperature of the heating coil. In calculating the transient thermal performance of a transformer winding, it is usually possible to neglect the effect of the rate of change of oil temperature on the temperature rise of the winding above the oil because of the relatively low thermal time constant involved in the transfer of heat from a transformer winding to the oil. For a heating coil having a considerably greater thermal time constant than a normal transformer winding, in calculating the transient thermal performance of the overload relay it is necessary to consider the influence of the rate of change of oil temperature upon the temperature rise of the heating coil over oil. This factor causes the temperature of the heating coil to be somewhat lower during short-time overloads than it would be otherwise and is the primary reason why a heating coil of this nature is so well suited to the control of short-time overloads.

The heating coil includes an assembly containing a loss-producing element and a temperature-sensitive element and having thermal capacitance. This assembly is surrounded by thermal insulation which also has distributed thermal capacitance. It will be assumed that the heating coil can be represented thermally by a suitable value of thermal capacitance and a suitable value of thermal resistance without distributed capacitance. From this assumption it follows that the heating coil will have a thermal time constant which can be determined readily as the product of the thermal capacitance and the thermal resistance. The thermal time constant also can be determined by making a heat run on the heating coil immersed in oil of constant temperature, with constant loss generated in the heating coil, and with the heating coil starting at the temperature of the oil. Under these circumstances the time constant can be determined as the length of time required to reach ultimate heating-coil rise over oil if the initial rate of rise were maintained or as the length of time required to reach 63 0 per cent of ultimate heating-coil rise over oil.

Development of Formula for Calculating the Transient Temperature Rise of a Heating Coil Over Top Oil When the Oil Temperature Is Increasing

KEY TO SYMBOLS

θ = temperature rise in degrees centigrade of heating coil over oil at any time, T

θ_u = ultimate temperature rise in degrees centigrade of heating coil over oil for the overload under consideration = $R \times P$

θ_b = temperature rise in degrees centigrade of heating coil over oil at start of overload

B_c = time constant of heating coil in minutes = $R \times C$

C = thermal capacity of heating coil in watts—minutes per degree centigrade

R = thermal resistivity of heating coil in degrees centigrade per watt

ϕ_u = ultimate temperature rise in degrees centigrade of transformer oil for the overload under consideration over the temperature at start of overload

B_0 = time constant of transformer oil in minutes

P = watts generated in relay during overload

T = time in minutes

ϵ = 2.718

F = factor allowing for effect of distributed thermal capacity of the heating coil

K = constant of integration

The watts loss generated in the heating coil must equal the sum of the watts absorbed and the watts transferred to the oil. When the oil temperature is rising the watts absorbed by the heating coil consist of two components:

1. Watts required to raise the temperature at the same rate as the oil temperature.

2. Watts absorbed because of its rate of rise over the oil temperature.

These relations can be expressed as follows:

$$P = C\frac{d\theta}{dt} + \frac{C\phi_u}{B_0}\left(\epsilon^{-\frac{T}{B_0}}\right) + \frac{\theta}{R} \tag{3}$$

If both sides are multiplied by R and θ_u is substituted for RP and B_c for RC

$$B_c\frac{d\theta}{dt} + \theta = \theta_u - \left(\frac{B_c\phi_u}{B_0}\right)\left(\epsilon^{-\frac{T}{B_0}}\right) \tag{4}$$

Solving for θ

$$\theta = \theta_u + K\left(\epsilon^{-\frac{T}{B_c}}\right) - \left(\frac{B_c}{B_0 - B_c}\right)\phi_u\left(\epsilon^{-\frac{T}{B_0}}\right) \tag{5}$$

The first term on the right-hand side of equation 5 is the ultimate heating-coil temperature rise over oil which will be realized if the overload is maintained until conditions are constant. The second term is an exponential transient of relatively high decrement. K can be determined by considering conditions at $T = 0$. The third term is a long time transient which represents an amount by which the temperature rise of the heating coil is depressed in rising oil on account of the thermal time constant of the heating coil.

In order to apply equation 5 to a heating coil with distributed thermal capacity, it is necessary to determine a thermal time constant which can be used to represent the performance of the relay. Such a time constant can be approximated closely by measuring the time constant by one of the usual methods previously outlined, and by inserting a correction factor F in equation 5 we obtain

$$\theta = \theta_u + K\left(\epsilon^{-\frac{T}{B_c}}\right) - \left(\frac{FB_c}{B_0 - FB_c}\right)\phi_u\left(\epsilon^{-\frac{T}{B_c}}\right) \tag{6}$$

Correction factor F can best be determined by comparing test measurements with equation 6.

When $T = 60$ or greater, the term $K\left(\epsilon^{-\frac{T}{B_c}}\right)$ can be neglected.

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The Accuracy of Measurements in Lumped *R-C* Cable Circuits as Used in the Study of Transient Heat Flow

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Synopsis: This paper deals with certain aspects of the accuracy of measurements on a lumped *R-C* cable, and contains definite suggestions as to the desirable number of lumps to be used in such measurements. The effect of capacitive leakage and the influence of sectioning (that is, the influence of the number of lumps) are considered in their relation to the accuracy of measurements of potential and current.

The increasing importance of lumped *R-C* circuits in heat-transfer research is pointed out, and the analogy between the flow of electricity in such circuits and the flow of heat, particularly unsteady-state or transient heat flow, is treated.

The investigations described in this report were carried out at Columbia University on the heat and mass flow analyzer, which is essentially an *R-C* circuit. The results can be used in the appraisal of errors encountered in heat flow and similar problems solved by the analogy method, that is, by lumped *R-C* circuits.

I. Introduction

THE conditions in lumped circuits of this type have been investigated previously.[1] However, these earlier investigations were based mainly on the assumption of ideal capacitors, that is, capacitors which do not leak. Such capacitors are not available. Actual experiments must always be carried out with capacitors which do leak; therefore an investigation of the errors caused by leaking capacitors is appropriate and should prove useful to the electrical engineer, because of the importance of network problems in general.

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Lumped *R-C* circuits have gained considerable importance in connection with the study of transient-heat-flow problems. The equations for potential and current distribution in a lumped *R-C* circuit on the terminals of which a voltage is suddenly impressed are identical with those for temperature rise and heat flow in a rod with insulated sides, the ends of which are suddenly exposed to a temperature difference. This analogy is the basis for a method of investigating transient-heat-flow problems, a method which has in recent years found increasing application. In fact, the investigations presented in this paper were prompted by the desire to know more about the accuracy of such a circuit in connection with the application to heat-transfer problems. Although in a number of instances it is possible to compare the results thus obtained with direct thermal measurements or mathematical analysis (see Figure 5 in reference 2, Figures 2 and 4 in reference 6, and Figure 6 in reference 5), in the majority of cases no direct comparison is possible. So far no systematical analysis of the sources of error in this method has been undertaken. This paper presents a first step toward such an analysis.

The application of *R-C* circuits to analyzing unsteady-state or transient-heat-flow problems has been discussed in a previous paper[2] by one of the authors. For the use of such circuits, which are the basis of the analogy method—devised first in Europe by C. L. Beuken[3]—he has developed a tool known as the "heat and mass flow analyzer." The analyzer, made possible largely through grants from the Research Corporation, has been set up at Columbia University, department of mechanical engineering.

Table I

Thermal Unit	Equivalent Electrical Unit
Temperature difference	Voltage
Heat flow	Electric current
Thermal resistivity	Electric resistivity
Thermal capacity	Electric capacitance

Since the laboratory was first opened in 1940, it has been used extensively for the investigation of heat-transfer problems too difficult to be solved mathematically. A number of these investigations have been published.[4-9]

The analogy method is based on two principles, namely:

1. The mathematical identity of equations for heat flow and certain electric circuits.

2. The replacing of a circuit with evenly distributed properties by one with lumped properties.

1. The first principle, which is exact, states that the mathematical equations for transient heat flow and for electric resistance–capacitance circuits are identical; hence, by solving an equivalent electrical problem the answer to the thermal problem may be obtained. The solution of the electrical differential equation can be made identical to that of the heat equation by making the proper insertion of equivalent electrical units as in Table I.

2. The second principle, which is an approximation, is that of replacing a differential equation by an equation of finite differences. In the analogy, this means that a body with evenly distributed resistance and capacitance is replaced by a body with "lumped" resistance and "lumped" capacitance. This procedure is common practice in certain fields of electrical engineering.

The study of any thermal problem by means of the analogy method consists of the following steps:

1. Setting up the analogous condition (calculation).

2. Building a resistance–capacitance circuit to represent the heat problem.

3. Subjecting this circuit to the appropriate analogous initial conditions (applying a given voltage at one end of the circuit, which is equivalent to exposure to a given temperature; or applying a current corresponding to a certain heat flow into a body, and so forth).

4. Measuring electrical units—voltage and currents—at points in the circuit analogous to those points at which temperatures and heat flow are to be measured in the body being subjected to heat flow.

5. Converting the results of the electric investigation into heat units (calculation).

A large variety of problems may be solved by the analogy method. The conditions for accuracy are different in each case. The voltage applied, the currents flowing, the duration of the experiment, the length of exposure of various parts of the circuit to higher voltages, even the atmospheric conditions in the laboratory—all influence the results.

For the investigation a particular type of problem was chosen, a type which may be considered as basic to the method in

general. This problem can be stated as follows: "An *R-C* circuit, initially at zero potential, is suddenly exposed to a potential difference, both ends of the circuit being connected to the supply system by noncapacitive resistances." In thermal terms this problem may be expressed as follows: "A wall, initially at zero temperature, is suddenly exposed on one surface to a finite higher value of temperature, while the ambient facing the other surface is held at the initial temperature. What is the temperature-time history at various points in the wall?" This problem is distinguished by the fact that no part of the circuit remains for long times at elevated potentials, and that the potential at the ends of the circuit remains constant. There are important thermal problems the analogous circuits of which do not show these conditions.

In the following presentation electrical units will be used; reference to equivalent heat units will be added as necessary.

II. Sources of Inaccuracy

In any type of problem to be solved on the analyzer, three sources of inaccuracy occur. They are listed here briefly, and the two which are inherent to the method are discussed individually in parts III and IV, as indicated in the list:

1. Inaccuracy due to leakage and stray currents (part III).
2. Inaccuracy due to lumping (part IV).
3. Inaccuracy in the instruments and in providing the given initial conditions.

The third group of inaccuracies is of course not inherent to this type of circuit. Neither, as far as the thermal aspect is concerned, is it inherent to the analogy method because the same type of errors would occur in measurements made and instruments used in direct thermal measurements. The objective error of the electric instruments used in the analyzer is between 0.3 and 0.5 per cent of the full-scale reading; the proportional error is therefore larger if the instruments are used on the lower part of their scales. In order to safeguard accuracy all measuring instruments in the equipment have several ranges. Thus the instruments can be used largely in the upper part of the scale, where the percentage error is smaller.

In addition to the objective errors there are those subjective ones due to inaccurate reading. The danger from this type of inaccuracy is of course increased by the fact that transients are to be observed, and therefore observations must be made while the needles of the instruments are moving more or less swiftly.

Finally, if changing initial conditions at the surface have to be represented—for instance, change of heat flow or temperature—the manual adjustment of the power supply to this condition may cause additional inaccuracies.

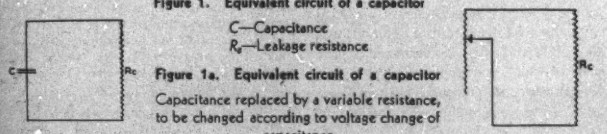


Figure 1. Equivalent circuit of a capacitor

C—Capacitance
R_c—Leakage resistance

Figure 1a. Equivalent circuit of a capacitor

Capacitance replaced by a variable resistance, to be changed according to voltage change of capacitance

III. Inaccuracy Due to Leakage and Stray Currents

Two causes of inaccuracy have to be considered here: leakage in the capacitors and stray or leakage current in the insulating parts of the circuit. It will be shown later that the two causes can be considered together. But first they will be discussed separately.

1. Capacitive Leakage

The capacitors which are used for representing the thermal capacity draw a leakage current after being loaded and, if left undisturbed, gradually discharge through their leakage resistance. If the capacitors were "ideal," they would draw no leakage current after being charged and would keep their charge indefinitely. In order to determine the inaccuracies introduced by the use of actual capacitors, a series of tests was conducted in which the results obtained from circuits with "ideal" capacitors were compared with the results from circuits with actual capacitors.

It is hard to obtain capacitors with specified leakage, and impossible to obtain ideal capacitors. Therefore, the capacitor, which has an equivalent circuit shown in Figure 1, is replaced by two parallel resistors, shown in the equivalent circuit, Figure 1a. The variable resistor represents the capacitance. At time zero the resistance is zero and gradually increases to infinity when the current is zero. When Figure 1a is considered, it becomes evident that the relative importance of the leakage changes greatly with the state of loading of the capacitor. In the case of the unloaded capacitor the equivalent resistance is very small; compared with this very small resistance the parallel leakage resistance, which is very high, can be neglected. As loading proceeds, the apparent resistance of the capacitor becomes larger, and thus the relative importance of the leakage resistance increases.

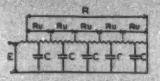


Figure 2. Equivalent circuit of a cable or of a semi-infinite wall

C—Capacitance
R_u—Useful resistance per lump
R—Total useful resistance
E—Over-all voltage

From these considerations it becomes evident that it is sufficient to investigate the steady state, that is, the condition with capacitors loaded to their steady-state potential. If in this case the leakage through the capacitor is within tolerable limits, then it is even more within these limits while the capacitor is at a lower voltage and drawing a heavier current.

Figure 2 shows the type of circuit which is to be investigated. R_u are the "useful" resistors, C the capacitors. It

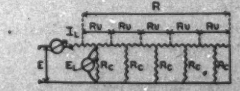


Figure 3. Circuit diagram for investigation of capacitance leakage in circuit Figure 2—steady state

R_c—Resistances equivalent to the leakage of capacitors
R_u—Useful resistance per lump
R—Total resistance
I_L—Current with leaking capacitors
E_L—Voltage with leaking capacitors
E—Over-all voltage

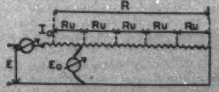


Figure 4. Circuit diagram. Nonleaking capacitors—steady state

E, R, R_u—Same meaning as in Figure 3
E_o—Voltage } with nonleaking "ideal"
I_o—Current } capacitors

is assumed that all sections are equal. This circuit is represented in steady state by the circuit (Figure 3) for actual—leaking—capacitors and by the circuit (Figure 4) for ideal—nonleaking—capacitors.

As mentioned previously, the investigations are carried out by comparing the results from the circuit shown in Figure 3 with those from the circuit shown in Figure 4. Two quantities are of interest in the investigations covered by this paper: voltage and current. On the electric analyzer these represent temperatures and rate of heat flow.

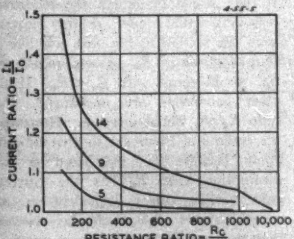


Figure 5. Current ratio, I_L/I_0, plotted as function of the resistance ratio, R_c/R_u. The numbers on the curves (14, 9, 5) indicate the number of sections involved

I_L—Current with leakage (Figure 3)
I_0—Current with no leakage (Figure 4)
R_c—Leakage resistance of capacitance
R_u—Useful resistance per lump

Let the insulation characteristic of the capacitor be expressed by τ. In symbols this would be written as $\tau = R_c C$. τ, which is called the capacitive time constant, has the dimensions of time; thus, if R_c is given in megohms and C in microfarads, τ will be in seconds.

The leakage resistance, R_c, of any capacitor can be expressed by:

$$R_c = \tau / C \text{ megohms} \qquad (1)$$

For capacitors of equal quality, the larger the capacitor the smaller will be its leakage resistance.

The product $R_c C$ for each section is the section time constant. Let this time constant be T. Then

$$T = R_c C \qquad (2)$$

By comparing equation 1 with equation 2 it can be seen that R_c/R_u and therefore I_L/I_0 and E_L/E_0 do not depend on the value of C. Thus:

$$\tau/T = R_c C/R_u C = R_c/R_u \qquad (3)$$

Let I_L be the current obtained for any given voltage in the circuit of Figure 3 and I_0 the current obtained with the same voltage in the circuit of Figure 4. The ratio I_L/I_0 of the two currents is plotted in Figure 5. This ratio depends on the relative value of R_c and R_u and on the number of sections. R_c/R_u is shown on the abscissa. Three curves are plotted; these are marked 14, 9, and 5, indicating the number of sections to which the curve refers. The larger the number of sections, the greater will be the current ratio I_L/I_0 and the more inaccurate will the method become. As R_c/R_u increases, the ratio I_L/I_0 decreases and approaches unity as R_c/R_u approaches infinity.

Example: Let the capacitor time constant $\tau = 50{,}000$ megohms $\times \mu f$ ($= 50{,}000$ seconds). Let each section have a resistance R_u of 0.9 megohm and a capacitance of 55.5 μf. Section time constant T is $T = 0.9 \times 55.5 = 50$ megohms $\times \mu f = 50$ seconds $\tau/T = 50{,}000/50 = 1{,}000$. The current ratio I_L/I_0 for 14 sections is then 1.055 (from Figure 5).

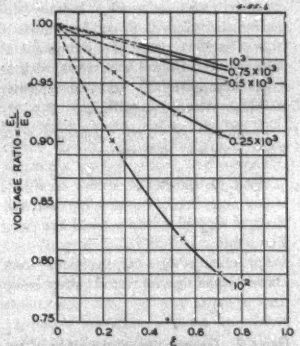


Figure 6. Voltage ratio, E_L/E_0, plotted against fractional resistance

($\xi = 0.5$ is, for example, the center of the resistance.) 14 sections. The figures on the curves (10^3, 0.5×10^3, and so forth) indicate the resistance ratio, R_c/R_u. The xs show points taken with nonuniform subdivision

In Figure 6 the voltages, E_L and E_0 of the same circuits are compared. The ratio of these voltages is different at various distances from the beginning of the circuits. On the abscissa the fraction of the total resistance R is plotted (see Figure 2). For example, $\xi = 0.5$ indicates the center of the total resistance. On the ordinate the voltage ratio, E_L/E_0 is plotted. E_L/E_0 is the ratio of the voltage obtained at any one point from circuit Figure 4 to that obtained at the same point from circuit Figure 3. The total number of sections was 14. The various curves refer to different resistance ratios R_c/R_u.

Figures 7 and 8 are similar to Figure 6 with the difference that in Figure 7 the total number of sections was nine and, in Figure 8, the total number of sections was five.

The same results are obtained in any experiments of this type (with ideal equipment) as long as T remains unchanged (see equation 2). The same results are obtained with large capacitors and small resistors as with small capacitors and large resistors. Equation 3 shows that the introduction of capacitor leakage does not modify this statement. Even with leaking capacitors the same accuracy or, of course, the same error, is reached with any value of T, independent of the distribution of T between resistance and capacitance. From this viewpoint, it becomes obvious that it is desirable to work with as few sections as possible, as may also be found qualitatively from consideration of the circuit of Figure 3.

It may be noted here that the requirements resulting from the investigations of

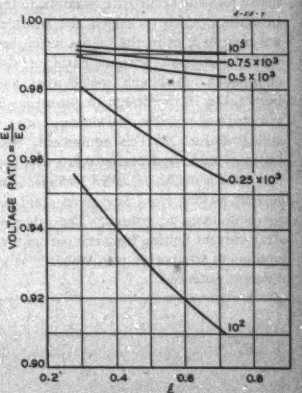


Figure 7. Voltage ratio, E_L/E_0, against fractional resistance

(For example, $\xi = 0.5$ is the center of the resistance.) Nine sections. The figures on the curves (10^3, 0.5×10^3, and so forth) indicate the resistance ratio, R_c/R_u

part IV are in the opposite direction, calling for many sections.

2. Equipment Leakage (Other Than Capacitive Leakage)

So far it has been assumed that the equipment other than capacitors is free from leakage. Figure 9 shows part of the

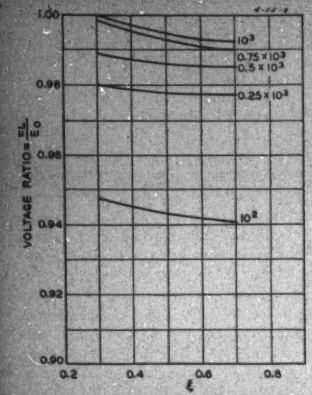


Figure 8. Voltage ratio, E_L/E_o, against fractional resistance

(For example, $\xi=0.5$ is the center of the resistance.) Five sections. The figures on the curves (10^3, 0.5×10^3, and so forth) indicate the resistance ratio, R_s/R_u

laboratory equipment. It is obvious that many leaks do occur—for example, in the insulating panels on which the resistors are mounted, or in the busses which are used to connect various parts of the equipment. Although special care has been taken in the design to get as small a leakage as possible, the leakage current still is finite. In this equipment, two types of undesired currents are flowing. One, which might be called leakage, is a current flowing from any given point in the equipment to ground. The other is stray current flowing from one part of the equipment to another part which is at a different potential.

The leakage current in the insulating part may be thought of as an additional current in the capacitor. The equipment leakage (not capacitor leakage) in each section may be thought of as being replaced by one leakage resistor R_B which is parallel to the leakage resistor R_c of the capacitor. The equivalent total leakage resistance per section R_L is to be found from $1/R_L=1/R_c+1/R_B$ (see Figure 10).

The value of R_B changes with temperature and atmospheric conditions. In dry conditions, and, with all sections connected, it amounts on the Columbia analyzer to approximately 150 megohms. R_B is of course independent of the capacitance and also of the time constant T of the section. Therefore equation 3 does not hold if equipment leakage is to be considered. It makes considerable difference how T—R_uC—is divided between capacitance C and resistance R_u. The influence of R_B on R_L is smaller if R_c is smaller; moreover small R_c means, with unchanged value of T, smaller values of R_u. Therefore, from the standpoint of leakage, it is desirable to work with as high a capacitance, and consequently as low a resistance, as possible.

Example: Let $T=60$; $\tau=50{,}000$; $R_B=3{,}000$ megohms; 14 sections.

Table II shows the values of R_L/R_u and of I_L/I_s for various possible combinations of R_u and C which yield the same $T(=60)$.

Fortunately the stray currents from one section of the circuit to another are so

Figure 9. General view of the electrical apparatus used in solving problems in three-dimensional heat flow by electrical analogy

Power photo

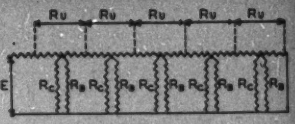


Figure 10. Equivalent-circuit leaking capacitors and leaking boards

R_u—Useful resistance
R_c—Leakage resistance of capacitors
R_B—Leakage resistance of board
E—Over-all voltage

small that they can be neglected here. If they would be larger, the following reasoning would apply: A stray current from one section to the next acts like a shunt for resistor R_u. A total resistance R_u' would result with $R_u'<R_u$. If all other conditions are unchanged, the ratio R_u'/R_s would increase. However, the circuits of Figures 5 to 8 would not apply, because they are based on the assumption that R_u has the correct value, while under consideration of stray currents R_u' would be smaller than the correct value of R_u. A number of graphs would have to be determined, each holding for one ratio of R_u/R_u'.

So far it has been assumed that all sections are of equal resistance. In the thermal problem this would mean that all sections are of equal thickness. It is of course possible to make nonuniform lumps. If, for example, a circuit with a total resistance of 1.2 megohms (equivalent perhaps to a wall 12 inches thick) has to be investigated, and 12 sections or lumps are available, it is possible either to make 12 lumps, each with a resistance of 0.12 megohm (one inch thick), or to make the first three or four lumps with a resistance of only 0.06 megohm each (one half inch thick) and increase the resistance (thickness) of the others accordingly, so as to again cover the entire resistance (thickness) of 1.2 megohms (12 inches). Any other distribution would also be possible. One case was investigated: that of three small sections at the beginning of the circuit and ten large sections at the end of the circuit. Each of the three small sections at the beginning of the circuit has one third of

Table II

C	R_u	R_s	R_L	R_L/R_u	I_L/I_o
150	0.40	333	300	.750	1.083
120	0.50	416	365	.730	1.086
90	0.667	555	470	.705	1.090
60	1.0	833	652	.652	1.098
30	2.0	1,667	1,075	.538	1.122
15	4.0	3,333	1,580	.395	1.160

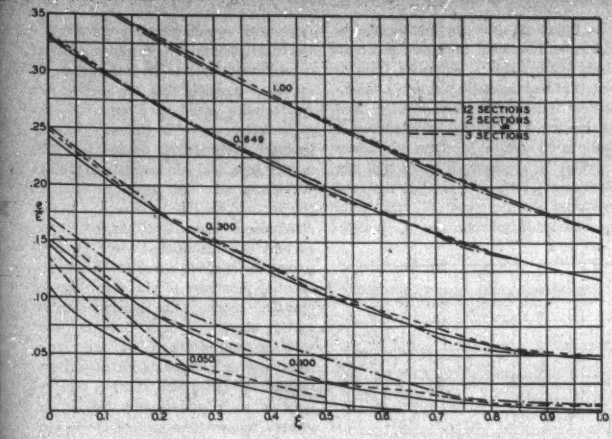


Figure 11. Voltage (temperature) rise in the circuit (wall)

Relative film resistance $m_h=2$, $m_c=1$. The figures on the curves indicate the dimensionless time, t/RC_1

the resistance and one third of the capacitance of the later sections. (The one-third resistance and capacitance correspond to one-third section thickness.) The results were compared with those of a uniform circuit of the same time constant. Two cases were investigated: one for $R_c/R_w=100$, the other for $R_c/R_w=250$. (R_c/R_w referring in both cases to one lump in the uniformly subdivided circuit.) The ratios I_L/I_e for evenly distributed sections were 1.49 ($R_c/R_w=100$) and 1.22 ($R_c/R_w=250$), respectively; the corresponding values for uneven lumps or sections were 1.48 and 1.21, respectively. The measured points for the temperatures are indicated in Figure 6 (by x).

All the circuits shown so far have been based on the assumption of zero film resistance on both the hot and cold surfaces. In this connection a word of explanation is necessary. The heat exchange between a hot surface and the cooler ambient is generally characterized by a "film conductance" value (expressed, for example, in Btu per hour, square foot, degrees Fahrenheit). The underlying concept is that the heat exchange, following Newton's law, is proportional to the temperature difference between the surface and the surrounding. Although in many instances this proportionality does not exist, the introduction of a film conductance value is helpful. In electrical terms, film conductance is represented by a noncapacitive resistance at the end of the circuit. Circuits having zero film resistances were chosen because they illustrate the worst possible conditions for accuracy. If the film resistances are not zero, then additional resistors have to be added: one on the "hot end" of the circuit, representing the film resistance of the hot surface, and one on the "cold end" of the circuit, representing the film resistance of the cold surface. If such additional resistances were applied, the voltage drop in that part of the circuit which represents the wall would be only a part of the total voltage drop. As a result, the ratio of the current with capacitors to that without capacitors would become smaller.

IV. Inaccuracy Due to Lumping

1. Concept

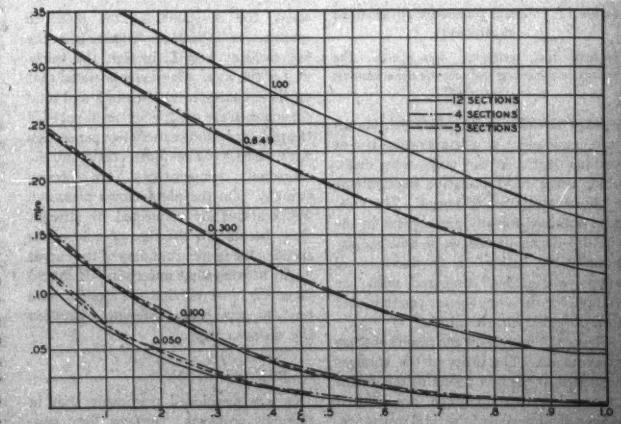
One could conceive as a theoretical limit of an equipment without any leakage, either in the capacitors or in the panels. None of the errors discussed in part III would occur, and yet the equipment would yield only approximate answers because of the errors due to lumping.

The selection of a finite number of lumps or sections instead of an infinite number is, mathematically speaking, equivalent to replacing a differential equation by an equation of finite differences. The main points of interest in this connection are the voltages, corresponding to the temperatures during the gradual heating up. In steady state the voltage–space distribution is theoretically a straight line; the actually measured points all fall on this line, independent of the number of sections used. During the heating-up period, however, more or less important discrepancies between the theoretical result and that obtained with only a few sections will occur.

In order to investigate the influence of the number of sections on the accuracy—from the viewpoint of "lumping"—it is necessary to know the theoretical curves of temperature rise. Such curves are not yet available; therefore, the curves obtained from tests in which 12 sections

Figure 12. Voltage (temperature) rise in the circuit (wall)

Relative film resistance $m_h=2$, $m_c=1$. The figures on the curves indicate the dimensionless time, t/RC_1



were used were considered to be sufficiently close to the theoretical value. This assumption is upheld by past experiments and also by the fact that no measured differences were observed between the curves taken with 15 and those with 12 lumps.

2. Procedure

The procedure for determining the influence of sectioning was as follows: the voltage rise at various points in the circuit—equivalent to a temperature rise at various depths in the wall—were measured, using in consecutive experiments a different number of lumps. The voltages obtained for any given point in the circuit—depth in the wall—and at any given time, using small numbers of lumps, were then compared with the voltage for the same space, position, and time obtained with 12 lumps.

Figures 11 to 14 show the results of these experiments. The ratios of the voltages measured at various points in the circuit to the impressed voltage are plotted against the fraction of the total resistance, as in Figure 6. The thermal parallel is, of course, fractional thickness and fractional temperature. Values of time as well as of resistance are plotted in dimensionless units. The dimensionless unit for time is t/RC_t and that for resistance or depth is $\xi = r/R = x/L$. Here t indicates the time in seconds after start of the experiment; R (as in part III) the total resistance in megohms; C_t the total capacitance in microfarads; r, in megohms, the resistance at the point in question; x, in feet, its distance from the hot surface; and L, in feet, the thickness of the wall. (It should be noted that on these charts, total resistance and total capacitance are used, whereas in part III the resistance and capacitance per section were used.) The lines between the measured temperatures are drawn straight. On the plots shown measured temperatures are connected by straight lines, because in the case of only a few sections the proper rounding of the curves might be somewhat uncertain. It should be noted, however, that the straight lines tend to accentuate differences between the various curves.

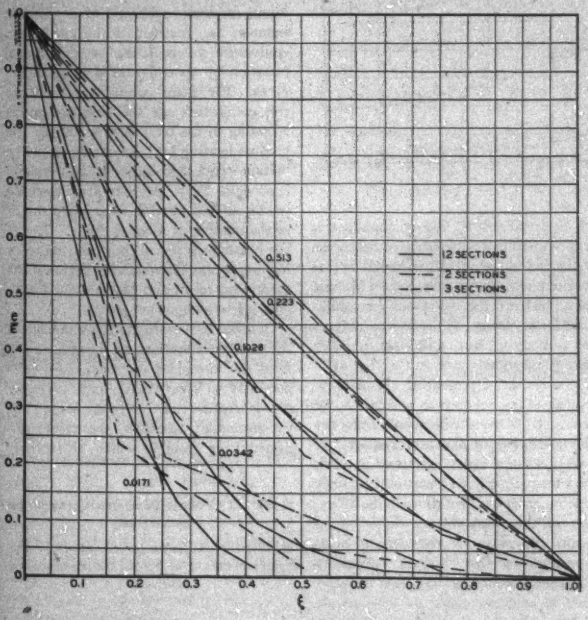


Figure 13. Voltage (temperature) rise in the circuit (wall)

Relative film resistance $m_b = m_c = 0$. The figures on the curves indicate the dimensionless time, t/RC_t

3. Film Conductance

It was mentioned previously that in thermal problems "surface film conductances," which are represented in the electrical problem by resistances without capacitance, have to be introduced. It appeared probable that the surface film conductance would have some influence on the errors caused by lumping. A preliminary investigation proved that this is the case and that worst conditions prevail for zero film resistance on both the hot and the cold surfaces. The film resistance in this connection is best expressed in dimensionless units by comparing the film resistance $(1/h)$ with the thermal resistance of the wall. In the electrical analogy the resistance representing the film $(1/h)$ is to be compared with the total resistance R of the circuit. The ratio of film-resistance to wall resistance is called the relative film resistance m. Symbolically, this is expressed by $m = 1/hR$, where $1/h$ is converted to ohmic units.

In extreme cases the wall can be of metal with high thermal conductivity and the ambient can be still air. In such cases the value of m can rise quite high, say to more than 1,000. With so high an m the temperature difference between hot and cold surface of the piece is at any time so small that the number of sections used has no measurable influence. In fact *measurable* differences occur only at fairly low values of m. Therefore, a series of tests was run, gradually increasing the values of m, that is, increasing the hot- and cold-surface relative film resistances. It was found that beyond $m_b = 6$ no appreciable voltage (temperature) differences occur within the circuit. Even for values of m in the order of magnitude of two the differences are not large. This can be seen by comparing Figures 11 and 12 with Figures 13 and 14. Figures 11 and 12 refer to $m_b = 2$, $m_c = 1$, while Figures 13 and 14 refer to $m_b = m_c = 0$.

In Figures 11 and 13 the results for two and three sections are compared with those for 12 sections (12 sections being assumed to be identical with the theoretical curve). In Figures 12 and 14 the results for four and five sections are compared with those for 12 sections.

By comparing the group of curves for $t/RC_t = 0.100$ (Figure 13) with those for $t/RC_t = 0.1026$ (Figures 13, 14) it becomes evident that the difference between the curves for few sections and those for 12 sections is smaller for large values of m. A number of experiments have been carried out using different combinations for m_b and m_c. For space economy, these cannot be reproduced here. It is sufficient to say that the differences between "many"

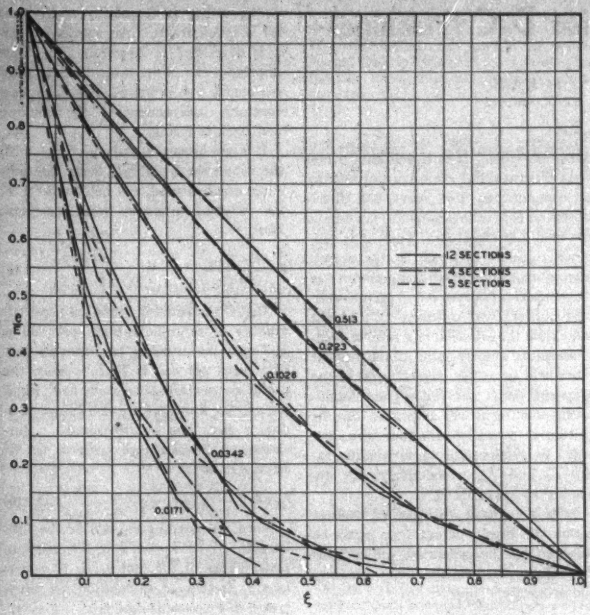


Figure 14. Voltage (temperature) rise in the circuit (wall)

Relative film resistance $m_h = m_e = 0$. The figures on the curves indicate the dimensionless time, t/RC_t

and "few" lumps were consistently smaller for large $m's$ than for $m_e = m_h = 0$. Generally speaking, m_e is of smaller influence than m_h.

4. Conclusions

1. Two or three lumps are not sufficient to represent a problem except for very approximate solutions or for values of t/RC_t at or near the steady state. The steady-state or near-steady-state t/RC_t would be small for low $m's$ in comparison with steady-state t/RC_t for large $m's$.

2. Five lumps give very good results except for relatively small values of t/RC_t.

3. In general a small number of lumps is sufficient if voltages (temperatures) at greater distance from beginning of the circuit (the hot surface) and at later times after start (that is, at higher values of t/RC_t) are necessary.

V. General Conclusions

In order to counteract the inaccuracies due to leakage, a small number of lumps is desirable. In order to counteract inaccuracies due to lumping, a large number of lumps is desirable. A practical medium is between six and nine lumps; then none of the influences become large.

The selection of nonuniform sections or lumps does not seem to influence the accuracy. Lumps can therefore be made so as to give a great number of readings in that part of the body to be investigated which is of greatest interest.

The preceding considerations hold only for the problem mentioned. Conditions may change in different types of problems, either adding resistors and capacitors to simulate two-dimensional heat flow, or in problems where parts of the circuits are kept at elevated voltages for some time.

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A Design Method for D-C Machines

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INTEREST in d-c machines in many phases of the war effort prompts the writers to present a method of design which has been found to be very useful and time saving. The method makes use of fundamental relationships in somewhat different forms and approaches the design from a different viewpoint than is ordinarily the case. The procedure has been in use for some time in the design of low-voltage aircraft motors and normal-voltage integral horsepower motors and generators. Comparative design and test results have shown good agreement.

The most common type of design problem is one which makes use of standard mechanical parts from which the required performance is realized by proper proportioning of the windings. Even though the rating required is a rather unusual one, it is rarely economically feasible to make a complete new design, mechanically and electrically. Or, if a new mechanical design is made, future requirements will make it necessary to use the same frame for other ratings.

If the mechanical design is fixed, dimensional details of the magnetic circuit (with the possible exception of stacking) are known, and the magnetization curve and rotational losses become known or can be calculated by conventional methods.

While the design method is developed and illustrated herewith for a series motor with commutating poles, the principles are applicable and can be extended easily to include shunt and compound machines.

Design Considerations

In the conventional design of a d-c motor, when the magnetization curve is given, the usual procedure is to select an operating point on the curve, thereby fixing the flux. On assuming a value of generated voltage, it is then possible to calculate the number of series conductors required in the armature winding. In order to check the performance of the machine, it is necessary to make a further assumption of armature current; this in reality involves an assumption of machine efficiency. As will be demonstrated later, the selection of an operating point on the magnetization curve fixed the ratio of field ampere-turns to armature ampere-turns per pole. It is a well-known fact that this ratio has an important bearing on commutation, iron losses, and distribution of copper losses, hence, heating in the field and armature. Thus, it is proposed to select this ratio at the outset, thereby fixing the operating point on the magnetization curve for a given full-load output (see Appendix I). At the same time the selection of a ratio of field-to-armature ampere-turns establishes the series-field turns per pole in terms of the armature turns per coil. The commutating-pole turns per pole also can be written in terms of armature turns per coil. Expressions for these winding ratios F_w and F_{wc}, respectively, are developed in Appendix II.

In a d-c motor the applied voltage minus the brush-contact drop must be balanced by the generated voltage plus the voltage drop in the series windings and armature. Thus

$$V - V_{BR} = E + I_a R_e \tag{1}$$

The generated voltage is

$$E = \left(\frac{2\phi P S_c \text{ rpm}}{a \times 60 \times 10^8}\right) T = BT \tag{2}$$

This is the usual form of the voltage equation, except that the total number of armature conductors has been replaced by its equivalent in terms of armature turns per coil (T) and commutator segments (S_c). As indicated in equation 2, E is dependent only on T, since the flux is already determined by selection of the operating point on the magnetization curve as discussed previously.

The series voltage drop is

$$I_a R_e = I_a (R_a + R_f + R_{cp}) \tag{3}$$

It is shown in Appendix III that the armature resistance (R_a) is a function of T^2 and that, when making use of the winding ratios, F_w and F_{wc}, the resistances of the series-field and commutating-pole windings are also functions of T^2.

Equation 3 then can be written

$$\begin{aligned} I_a R_e &= I_a r_e T^2 \\ &= (I_a T r_e) T \\ &= \left[\frac{(NI)_F}{F_w}\right] r_e T \\ &= C r_e T \end{aligned} \tag{4}$$

C becomes known upon selection of the operating point on the magnetization curve, and r_e is essentially a constant for a given frame. An expression for r_e is developed in Appendix III. It is important to note that, having fixed reasonable values for F_w and F_{wc}, r_e is a constant, independent of the winding and machine rating.

It is now apparent that equation 1, with the values for E and $I_a R_e$ from equations 2 and 4 substituted, can be solved for T, the required armature turns per coil. Thus

$$T = \frac{V - V_{BR}}{B + C r_e} \tag{5}$$

Also, if the winding ratios are used, the number of series-field turns per coil is $F_w T$ and the number of commutating-pole turns per coil is $F_{wc} T$. Since the useful copper areas for each field winding and the armature are also known, conductor sizes can be determined. Furthermore, the armature current can be calculated as

$$I_a = C/T \tag{6}$$

Since the winding as well as the full-load current are known now, the complete performance of the motor can be calculated. Details of calculation are illustrated in the sample design.

In conclusion, the foregoing information has proved useful in instances where the design problem involves determination of winding details and performance when the mechanical design is fixed. The method involves no new fundamental theory but yields a design directly wherein certain important factors are incorporated in such a way as to insure their ultimate realization in the performance of the machine. In addition, calculated performance will be in general in much better agreement with test results than is the case in conventional methods.

Appendix I. Determination of Operating Point on Magnetization Curve

It is assumed that the open-circuit magnetization curve and rotational-loss data, such as are shown in Figure 1, are known from test of previous designs in the particular frame in question or have been calculated by conventional methods.

The power developed in the armature of a

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d-c machine is EI_a and must equal the power output (W) plus the rotational loss (RL). The latter includes core losses as well as friction and windage and stray load loss. Thus

$$W' = W + RL = EI_a \tag{7}$$

but

$$E = \frac{\phi PZ \text{ rpm}}{a \times 60 \times 10^8} \tag{8}$$

hence

$$W' = \frac{\phi P \text{ rpm } ZI_a}{a \times 60 \times 10^8} \tag{9}$$

The armature ampere-turns per pole, $(NI)_a$, are equal to $ZI_a/2aP$. Equation 9 then may be written

$$W' = \frac{\phi P^2 \text{ rpm}}{3 \times 10^8} \times (NI)_a \tag{10}$$

It is desired to use the ratio of field ampere-turns to armature ampere-turns per pole, γ, as a starting point in the design. Hence, if $(NI)_a$ in equation 10 is replaced by $\gamma/(NI)_f$ and if terms are rearranged

$$\phi(NI)_f = \frac{W'}{\text{rpm}} \times \frac{\gamma}{P^2} \times 3 \times 10^8 = A \tag{11}$$

Thus, the operating point on the magnetization curve is fixed by the output of the machine, speed, number of poles, and the ampere-turn ratio. The choice of a suitable value for γ for a given design will depend on the type of machine and the application. The range is usually from 0.6 for series machines to 1.25 for shunt machines. A good average value for shunt or compound machines with commutating poles is 1.0.

Every point on the magnetization curve corresponds to a certain value of $\phi \times (NI)_f$. A particular value is required to meet the rating requirements. One obvious method for determining the operating point would be to plot a curve of $A = \phi(NI)_f$ versus $(NI)_f$ and read from this curve the value of $(NI)_f$ for the particular value of A which is required. In obtaining such a curve, the full-load magnetization curve should be used.

The flux per pole (ϕ) in equation 11 is the full-load value and will be less than that obtained from the no-load curve for given field excitation due to the demagnetizing effects of armature reaction. If the brushes are shifted from the no-load neutral, the direct demagnetizing ampere-turns of the armature are

$$(NI)_{dm} = \frac{\theta}{90}(NI)_a = \frac{\theta}{90}\frac{(NI)_f}{F_w} \tag{12}$$

Various methods are available for determining the demagnetizing effect of the cross-magnetizing ampere-turns, most of which are quite tedious to apply and not well adapted for use in a design method such as this. For small machines, a simple expression

$$(NI)_{dm} = \frac{1.1}{10^4}\frac{(NI)^2_f}{F_w} \tag{13}$$

has been found to give quite satisfactory results. If equations 12 and 13 and the no-load magnetization curve are used, it is possible to construct full-load magnetization curves for any given values of θ and γ. However, as illustrated later in the sample design, there is little need for obtaining the full-load curve, since the required point on the curve can be calculated rather easily.

Appendix II. Winding Ratios, F_w and F_{wc}

The winding ratios F_w and F_{wc} are defined as the ratios of series-field turns per pole to armature turns per coil and commutating-pole turns per pole to armature turns per coil, respectively. Thus, F_w is equal to N_f/T and F_{wc} is equal to N_{cp}/T. An expression for F_w can be found in terms of known quantities from the definition of γ as

$$\gamma = \frac{(NI)_f}{(NI)_a} = \frac{N_f I_a}{\frac{ZI_a}{2aP}} = \frac{aP}{S_c}\frac{N_f}{T} \tag{14}$$

or

$$\frac{N_f}{T} = F_w = \frac{\gamma S_c}{aP} \tag{15}$$

In a similar manner, F_{wc} is found to be

$$F_{wc} = \frac{N_{cp}}{T} = \frac{\sigma S_c}{aP} \tag{16}$$

Where σ is the ratio of commutating-pole ampere-turns per pole to armature ampere-turns per pole. A common value for σ is about 1.25.

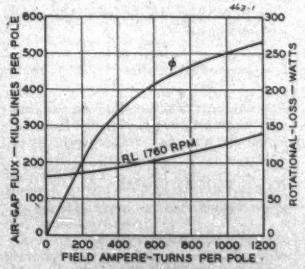

Figure 1. Magnetization and rotational-loss curves

Appendix III. Resistances in Terms of T

(a). Armature resistance, R_a.

The usual expression for the resistance of the armature at 25 degrees centigrade, in terms of resistivity, number of series conductors, and cross-section area of each, is

$$R_a = \frac{0.880 l_a Z}{CM_a a^2} \text{ ohms} \tag{17}$$

If Z is written in terms of T and the number of commutator segments, and the area of each conductor is replaced by the useful slot area divided by the number of conductors per slot, equation 17 becomes

$$R_a = \frac{0.880 l_a (2S_c T)}{\left(\frac{S_c CM_{ss}}{2S_c T}\right) a^2} = \left[\frac{3.52 l_a S_c^2}{S_c CM_{ss} a^2}\right] T^2 \text{ ohms} \tag{18}$$

(b). Series-field resistance, R_f.

The series-field resistance at 25 degrees centigrade is

$$R_f = \frac{0.880 l_f N_f P}{CM_f} \text{ ohms} \tag{19}$$

Again the area of each conductor is replaced by an expression involving the useful copper area for the field winding, and $F_w T$ is substituted for N_f. Then

$$R_f = \frac{0.880 l_f P (F_w T)}{CM_{sf}/F_w T} = \left[\frac{0.880 l_f P F_w^2}{CM_{sf}}\right] T^2 \text{ ohms} \tag{20}$$

(c). Commutating-pole-winding resistance, R_{cp}.

The resistance of the commutating-pole windings at 25 degrees centigrade is

$$R_{cp} = \frac{0.880 l_{cp} N_{cp} P_c}{CM_{cp}} \text{ ohms} \tag{21}$$

When similar substitutions are made to those suggested in b, equation 19 becomes

$$R_{cp} = \left[\frac{0.880 l_{cp} P_c F_{wc}^2}{CM_{ss}}\right] T^2 \tag{22}$$

The summation of equations 18, 20, and 22 is the total series-winding resistance of the machine at 25 degrees centigrade, R_s. Hence

$$R_s = R_a + R_f + R_{cp} = \left[\frac{3.52 l_a S_c^2}{S_c CM_{ss} a^2} + \frac{0.880 l_f P F_w^2}{CM_{sf}} + \frac{0.880 l_{cp} P_c F_{wc}^2}{CM_{ss}}\right] T^2 \tag{23}$$

$$= r_s T^2 \tag{24}$$

In using equation 24 a correction factor for temperature should be applied, since the expression as given is at 25 degrees centigrade.

Numerical Example

If the basic equations derived in the foregoing discussion are used, the details of a typical design will be illustrated. It is required to determine the winding and full-load performance for a 250-volt 2.0-horsepower 1,800-rpm d-c series motor in a standard National Electrical Manufacturer's Association frame 224.

The necessary mechanical details for the design, taken from previous designs in the same frame, are as follows:

Number of main poles (P) = 2
Number of commutating poles (P_c) = 1
Mean length of turn in main field (l_f) = 18.0 inches
Available copper area per coil in main field (CM_{sf}) = 1,400,000
Mean length of turn in commutating-pole winding (l_{cp}) = 11.5 inches

Available copper area per coil in commutating-pole winding (CM_{sc}) = 1,000,000 circular mils

Number of armature slots (S_a) = 29

Number of commutator segments (S_c) = 58

Mean length of armature conductor (l_a) = 8.50 inches

Available copper area per slot CM_{ss} = 100,000 circular mils

The open-circuit magnetization curve and rotational-loss data for this particular frame are given in Figure 1.

From the rotational-loss curve, a preliminary estimate of rotational loss for this motor is made as 130 watts. The output is 2.0 horsepower or 1,492 watts. Thus, when equation 7 is used

$$W' = W + RL = 1{,}492 + 130 = 1{,}622 \text{ watts}$$

Next, a suitable value of the ampere-turn ratio (γ) is chosen as 0.87. Then, if equation 11 is used

$$A = \frac{W'}{\text{rpm}} \times \frac{\gamma}{P^2} \times 3 \times 10^9$$

$$= \frac{1{,}622}{1{,}800} \times \frac{0.87}{4} \times 3 \times 10^9$$

$$= 0.588 \times 10^9 = \phi \times (NI)_F$$

If the material following equation 11 is kept in mind, the full-load flux per pole (ϕ) and full-load ampere-turns per pole in the field $(NI)_F$ can be determined now. The full-load magnetization curve will be somewhat below that shown in Figure 1 and approximately 1,100 ampere-turns will be required to produce a flux per pole of 520,000 lines. The product of these two figures is essentially the required value of A.

To determine demagnetizing ampere-turns it is necessary to consider only the demagnetizing effect of the cross-armature ampere-turns, since the angle of brush shift θ is zero. Thus, from equation 13 the demagnetizing ampere-turns per pole are $1.1 \times (1{,}100)^2/0.87 \times 10^{-4}$ or 153. Subtracting this from the original value of $(NI)_F$ gives 950 ampere-turns, and the corresponding value of flux from the magnetization curve is 495,000. But $1{,}100 \times 495{,}000$ does not equal 0.588×10^9, and it is apparent that $(NI)_F$ must be increased. Let the gross field ampere-turns be 1,170. Then the demagnetizing ampere-turns are 160, the net field excitation is 1,010 and the flux is 503,000. The product of 1,170 and 503,000 gives the required value for A. Thus, the full-load operating point on the magnetization curve has been fixed. Now the preliminary estimate of rotational loss can be revised on the basis of a more accurate knowledge of the field ampere-turns, and the aforementioned process can be repeated if more accuracy is desired.

The foregoing procedure for determining the full-load flux and field excitation at first may seem rather complicated and time consuming. However, it has been found that after a little practice the operation becomes very simple and fast.

The next step is to calculate the winding ratios F_a and F_{sc} from equations 15 and 16

$$F_{sc} = \frac{\gamma S_c}{aP} = \frac{0.87 \times 58}{2 \times 2} = 12.6$$

$$F_{sc} = \frac{rS_c}{aP} = \frac{1.25 \times 58}{2 \times 2} = 18.1$$

The resistance term r_a can be determined now from equation 23

$$r_a = \frac{3.52 l_a S_c^2}{S_c C M_{ss} a^2} + \frac{0.88 l_F P F_{sc}^2}{C M_{SF}} + \frac{0.88 l_{cp} P_c F_{sc}^2}{C M_{sc}}$$

$$= \frac{3.52 \times 8.5 \times (58)^2}{29 \times 100{,}000 \times 4} + \frac{0.88 \times 18 \times 2 \times (12.6)^2}{1{,}400{,}000} + \frac{0.88 \times 11.5 \times 1 \times (18.1)^2}{1{,}000{,}000} = 0.01563$$

For an average operating temperature of 65 degrees centigrade r_a is 0.018.

The constants B and C are calculated from equations 2 and 4. Thus

$$B = \frac{2\phi P S_c \text{ rpm}}{a \times 60 \times 10^8} = \frac{2 \times 503{,}000 \times 2 \times 58 \times 1{,}800}{2 \times 60 \times 10^8} = 17.5$$

and

$$C = \frac{(NI)_F}{F_a} = \frac{1{,}170}{12.6} = 93.0$$

The required number of armature turns per coil is obtained from equation 5. A brush-contact drop of two volts is assumed

$$T = \frac{V - V_{BR}}{B + Cr_a} = \frac{250 - 2}{17.5 + 93 \times 0.018} = 13$$

The armature current can be calculated now from equation 6.

$$I_a = \frac{C}{T} = \frac{93}{13} = 7.15 \text{ amperes}$$

The number of field turns and commutating-pole turns per pole is obtained by multiplying F_a and F_{sc}, respectively, by T. Thus

$$N_F = F_a T = 12.6 \times 13 = 164$$

and

$$N_{cp} = F_{sc} T = 18.1 \times 13 = 235$$

The required conductor size in the armature winding is obtained from the useful slot area and the number of conductors per slot

$$CM_a = \frac{CM_{ss} \times S_c}{2 S_c T} = \frac{100{,}000 \times 29}{2 \times 58 \times 13} = 1{,}925 \text{ circular mils.}$$

This wire size is between numbers 17 and 18 (American wire gauge), and a choice must be made between reducing the number of turns slightly and using number 17 or using number 18 and not filling the slot. Here the former choice is made. Thus, a 12½-turn winding using number 17 wire (2,048 circular mils) is adopted. The corrected number of armature conductors is

$$Z = 2 S_c T = 2 \times 58 \times 12.5 = 1{,}450$$

Since the value of T was reduced slightly, the series-field turns must be reduced also if the assumed value of γ is to be maintained. However, this will result in somewhat higher speed than originally assumed. Thus, again there are two alternatives, of which the former will be used. Then

$$N_F = 12.6 \times 12.5 = 160$$

and

$$N_{cp} = 18.1 \times 12.5 = 225$$

The conductor size for the series field is CM_{SF} divided by N_F and is equal to 1,400,000/160 or 8,750 circular mils.

Use three number 16 wires in parallel giving an equivalent conductor of 7,750 circular mils. For the commutating pole use

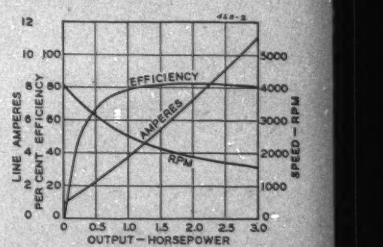

Figure 2. Performance curve for a 250-volt 2.0-horsepower 1,800-rpm d-c series motor

220 turns of two number 16 wires equivalent to 5,166 circular mils.

In order to check the motor performance using the aforementioned winding, the winding resistances are calculated in the usual manner

$$R_a = \frac{0.88\ l_a Z}{a^2 C M_a} = \frac{0.88 \times 8.5 \times 1{,}450}{4 \times 2{,}048} = 1.325 \text{ ohms at 25 degrees centigrade}$$

$$R_a(\text{hot}) = 1.15 \times 1.325 = 1.52 \text{ ohms}$$

$$R_{cp} = \frac{0.88 l_F N_F P}{C M_F} = \frac{0.88 \times 18 \times 160 \times 2}{7{,}750} = 0.645 \text{ ohm at 25 degrees centigrade}$$

$$R_F(\text{hot}) = 1.15 \times 0.645 = 0.75 \text{ ohm}$$

$$R_{cp} = \frac{0.88 l_{cp} N_{cp} P_c}{C M_c} = \frac{0.88 \times 11.5 \times 220 \times 1}{5{,}166} = 0.431 \text{ ohm at 25 degrees centigrade}$$

$$R_{cp}(\text{hot}) = 1.15 \times 0.431 = 0.49 \text{ ohm}$$

and the total series resistance is

$$R_s(\text{hot}) = R_a(\text{hot}) + R_F(\text{hot}) + R_{cp}(\text{hot}) = 2.76 \text{ ohms}$$

For full-load armature current of 7.15 amperes, the $I_a R_s$ drop is 19.7 volts. Assuming a brush-contact drop of two volts, the generated voltage is 228.3 volts.

At this point the field ampere-turns, armature ampere-turns, and their ratio can be calculated and the full-load flux can be checked before determining the speed. Thus

$$(NI)_F = I_a N_F = 7.15 \times 160 = 1{,}143$$

$$(NI)_a = \frac{ZI_a}{2aP} = \frac{1{,}450 \times 7.15}{2 \times 2 \times 2} = 1{,}297$$

Inverter Action on Reversing of Thyratron Motor Control

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Synopsis: Thyratron control of d-c motors offers a fast and smooth braking or reversal which is finding wider application in industry as the characteristics become better known.

With proper control the rectifier circuit, which normally supplies power to the armature of the motor, can be operated as an inverter to decelerate the motor by regenerating the rotational energy of the motor and its load into the a-c system. The circuit then shifts to rectifier operation to accelerate the motor and load to the preset speed in the reverse direction.

The motor-armature current can be held very nearly constant over the full reversal operation of deceleration and acceleration at a value which can be made less than the rated motor current. Test results and theory show that the motor's inherent reactance is sufficient for inverter operation, and, that during normal inversion, commutation of the tubes is not difficult.

In addition, inversion can be utilized to bring the motor to a stop more efficiently than by plugging and more rapidly and efficiently than by dynamic braking.

A GREAT many of the mechanized operations carried on in the industrial field call for a reversal of the mechanism by its motive power which is commonly an electric motor. In nearly all cases this reversal must not impose a severe strain on the mechanism nor demand an excessive overload from the power lines. In many of these reversing drives, particularly where they are of a cyclic nature, the reversal time is lost time and must be kept to a minimum consistent with the rating of the motor. Many of these drives call for the flexibility of the d-c motor. The d-c motors are supplied commonly from either a d-c shop bus or a motor generator set. However, an increasing number of d-c-motor applications are using the thyratron-tube rectifier to give a wide range of control, including a fast and smooth reversal.

The motor in a Ward Leonard drive is reversed by reversing the generator voltage and the current in the loop circuit. The thyratron-tube rectifier operating a motor in some respect is comparable with the Ward Leonard drive, but it has at least one important difference. The rectifier, unlike the generator, is a unidirectional conductor. It will conduct current in only one direction. Therefore, if the rectifier output voltage is reduced, the generated voltage of the motor cannot reverse the current through the circuit. Since the current through the motor-armature circuit must be reversed to reverse the direction of the motor torque, the armature connections must be reversed mechanically with respect to the tube circuit. To reverse connect the rotating motor armature suddenly into the "full-on" rectifier would amount to plugging with short-circuit current. This would be, to say the least, highly undesirable from the standpoint of the tubes, motor commutation, and the connected load. However, by proper control the tube circuit may be made to invert the d-c power generated by the motor into the a-c lines at a controlled rate.

It is not the intent of this paper to discuss the general theory nor to state a rigorous analysis of inversion, but to give a general description of the principle of inversion operating from the generated voltage of a d-c motor into the voltage of the a-c line and some means of controlling

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$$\gamma = \frac{(NI)_F}{(NI)_a} = 0.881$$

Demagnetizing ampere-turns

$$(NI)_{dm} = 1.1 \times 10^{-4} \times \frac{(1{,}143)^2}{0.881} = 163$$

and the net field ampere-turns, $(NI)'_F$ are 980.

The full-load flux, ϕ, is 500,000 lines per pole (from curve Figure 1). When the voltage equation is used, the speed is

$$\text{rpm} = \frac{Ea \times 60 \times 10^8}{ZP\phi} = \frac{228 \times 2 \times 60 \times 10^8}{1{,}450 \times 2 \times 500{,}000} = 1{,}885$$

Note that the speed is somewhat higher than originally assumed, since the 12½-turn armature winding was used instead of the 13-turn winding.

The power developed in the armature is EI_a or 1,633 watts, and, from Figure 1, the rotational loss is approximately 145 watts. The motor output is then 1,488 watts, the input is 1,788 watts, and the efficiency is 83 per cent.

Test results on a motor using the aforementioned winding design are shown in Figure 2. The full-load current was 7.18 amperes, and the efficiency was 82.5 per cent. The calculated rpm was slightly high, as the test shows 1,870 rpm.

Although the winding details as shown previously are complete, it is usually desirable to check on the distribution of copper losses, current density in brushes, flux densities in various parts of the magnetic circuit, and reactance voltage of commutation.

List of Symbols

a = parallel paths in armature windings
CM_{sa} = circular mils per slot in armature
CM_{ac} = circular mils per coil in commutating winding
CM_{SF} = circular mils per coil in series-field winding
E = generated voltage in armature winding
F_w = winding ratio (for motor)
F_{pc} = winding ratio for commutating poles
I_a = armature current, amperes
I_F = field current, amperes
l_a = mean length of armature conductor
l_F = mean length of turns in series-field coil
l_{cp} = mean length of turn in commutating-field coil
N_{cp} = commutating-pole turns per pole
N_F = series-field turns per coil
P = number of main poles
P_c = number of commutating poles
R_a = armature resistance
R_{cp} = commutating-field resistance
R_F = series-field resistance
R_e = total series resistance
RL = rotational losses
rpm = speed in revolutions per minute
S_c = number of commutator segments
S_a = number of armature slots
T = armature turns per pole
V = applied volts
V_{BB} = brush-contact drop in volts
W = machine output in watts
γ = ratio of main-field ampere-turns per pole to armature ampere-turns per pole
σ = ratio of commutating-field ampere-turns per pole to armature ampere-turns per pole
ϕ = armature flux per pole

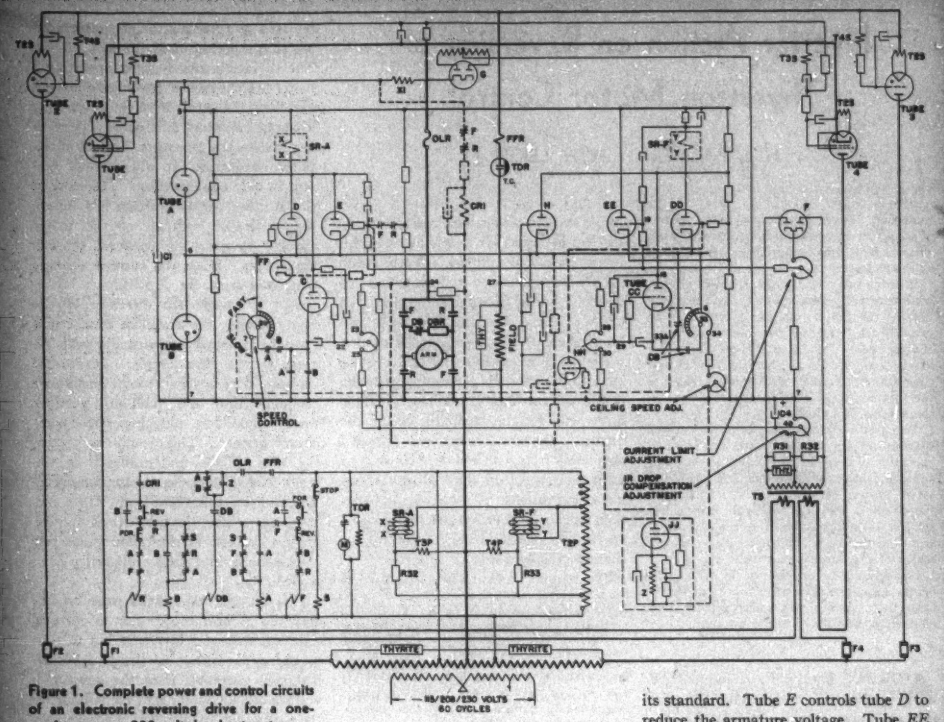


Figure 1. Complete power and control circuits of an electronic reversing drive for a one-horsepower 230-volt d-c shunt motor

this operation. Inversion is discussed from the standpoint of its usefulness in decelerating the thyratron-controlled d-c motor.

Brief Description of General Control

The method of controlling the inverter depends upon the type of rectifier circuit that is used, the method of controlling the thyratron grids, and the performance that is desired. The discussion of the circuit arrangement for the control of the inverter operation will be limited in this paper principally to one example. Since only inverter operation is to be covered here, the circuit used as an example is one the operation of which, except for inversion, was described quite thoroughly in a previous AIEE paper.[1] The complete control circuit is given in Figure 1.

Briefly, this control consists of two conventional biphase half-wave thyratron rectifiers and their associated control. Both rectifiers are operated from a single-anode transformer, one supplying the armature of the motor and the other supplying the field. The grid control of the thyratrons is by means of saturable reactor phase-shifting bridges. A small auxiliary thermionic rectifier supplies a d-c voltage, which is held constant by a pair of voltage regulator tubes, *A* and *B*, for the operation of the control vacuum tubes and for saturating the reactors.

The saturation of the armature and field saturable reactors *SR-A* and *SR-F* is controlled by two triodes, *D* and *DD*. Two voltage-amplifier tubes, *C* and *CC*, compare a portion of the armature and field voltages with an adjustable portion of a fixed voltage used as a standard and control tubes *D* and *DD* in the proper sense to regulate the armature and field voltages in proportion to the adjustments of the standards. These adjustable standards are the two speed-control potentiometers which are ganged together and so constructed and connected that they give the proper sequence of armature and field control.

Two other voltage amplifiers, tubes *E* and *EE*, compare a voltage proportional to the motor-armature current with two other fixed standards, each operating only when this current signal rises above its standard. Tube *E* controls tube *D* to reduce the armature voltage. Tube *EE* controls tube *DD* to raise the field voltage, but, since the standard of tube *EE* is slightly lower than that of tube *E*, it operates at a slightly lower current signal. The results are that, on overload of the motor, the field is strengthened before the armature voltage is reduced, and that, during acceleration of the motor, the armature voltage rises to full value before the field is permitted to weaken. The voltage proportional to the armature current is obtained by rectifying the secondary voltage of a current transformer, *T5*, the two primaries of which are connected in the anode circuits of the two armature thyratrons. It is this part of the circuit which holds the output current of the rectifier practically constant during acceleration of the motor.

General Description of Inverter Action on Reversal

As was pointed out earlier, the case of a motor driven from a rectifier is not analogous to the normal operation of a generator driving a motor, because the current cannot reverse through the rectifier. A somewhat analogous operation of

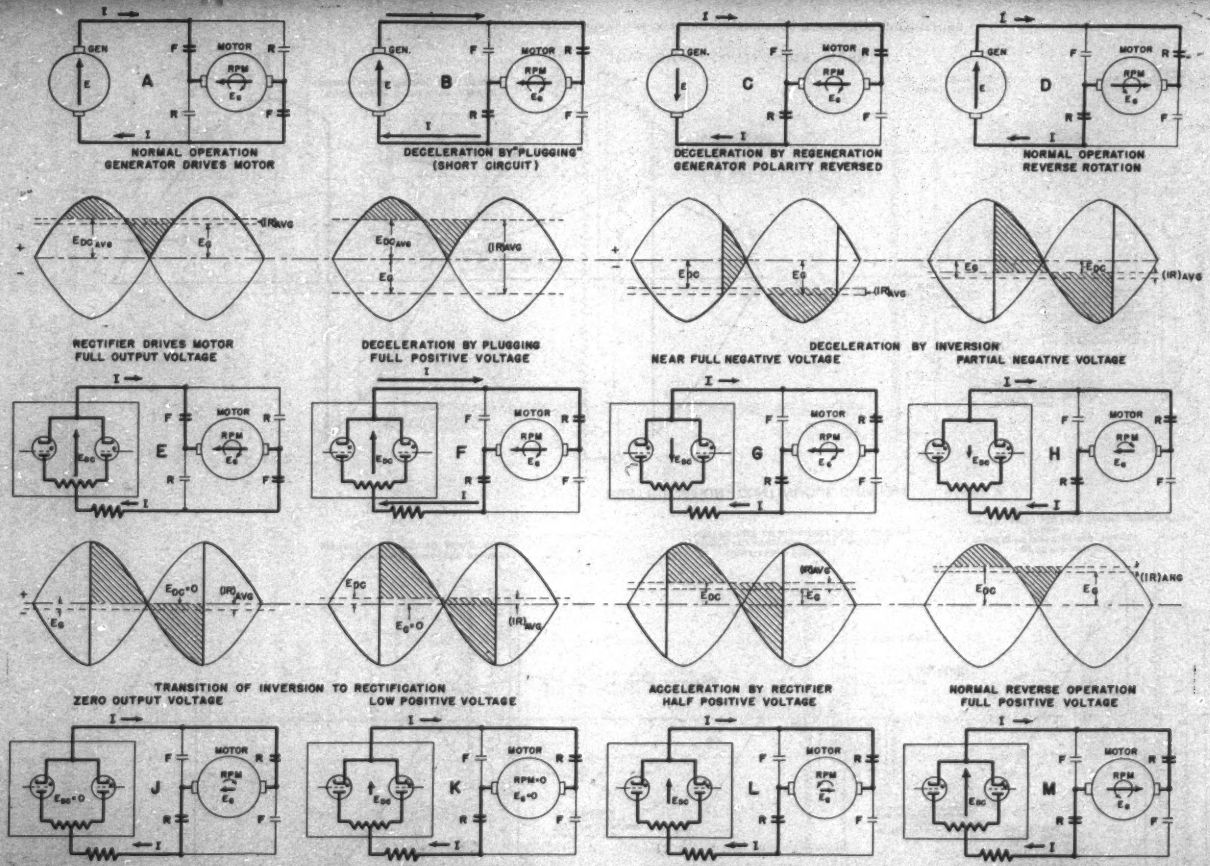


Figure 2. Diagrammatic representation of d-c motor reversal with constant shunt field

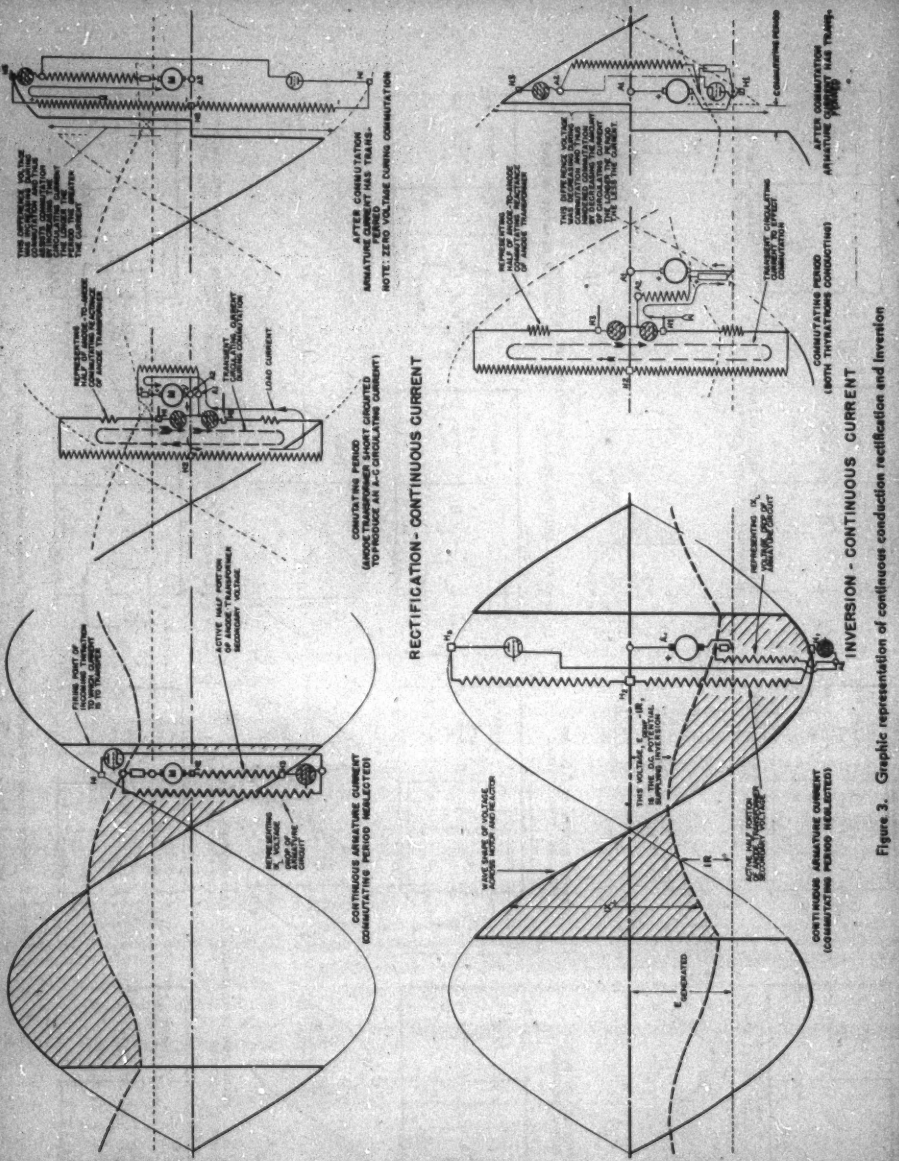

RECTIFICATION - CONTINUOUS CURRENT
INVERSION - CONTINUOUS CURRENT
CONTINUOUS ARMATURE CURRENT (COMMUTATING PERIOD NEGLECTED)
CONDUCTING PERIOD (MOMENTARY SHORT CIRCUIT TO PRODUCE AN A-C CIRCULATING CURRENT)
LOAD CURRENT
AFTER COMMUTATION ARMATURE CURRENT HAS TRANSFERRED
NOTE: ZERO VOLTAGE DURING COMMUTATION
COMMUTATING PERIOD (BOTH THYRATRONS CONDUCTING)
E GENERATED

Figure 3. Graphic representation of continuous conduction rectification and inversion

a generator driving a motor can be drawn as pictured in diagrams *A* to *D* in Figure 2.

A study of these figures will point out that, if the generator voltage is left unchanged, and the motor-armature connections are reversed, plugging and short-circuit current are the results; whereas, if the polarity of the generator voltage is reversed before the reverse contactors to the motor armature are closed, and if the generator voltage is made lower than the generated voltage of the motor, regenerative braking results.

The remainder of the diagrams, *E* to *M*, in Figure 2 represent simple biphase grid-controlled thyratron rectifiers supplying the armature of a d-c motor and operating under various stages of reversal. The motor field and all control is left out for simplicity. For the present the field excitation is assumed constant at its

RECTIFICATION (DISCONTINUOUS PULSES OF ARMATURE CURRENT)
INVERSION (DISCONTINUOUS PULSES OF ARMATURE CURRENT)
ANODE TRANSFORMER
ARMATURE COUNTER EMF
INSTANTANEOUS INVERSE VOLTAGE
ZERO LINE
REPRESENTING IR DROP
REPRESENTING IR DROP DURING BUILD-UP OF FLUX
SHAPE OF VOLTAGE IMPRESSED ACROSS ARMATURE TERMINALS
SHAPE OF CURRENT PULSE THROUGH ARMATURE
REPRESENTING VOLTAGE DROP ACROSS RESISTANCE OF ARMATURE DURING FLUX BUILD-UP
REPRESENTING ARC DROP OF THYRATRON (EQUALITY EXAGGERATED IN PROPORTION TO OTHER VOLTAGES)
ARMATURE COUNTER EMF PLUS IR DROP
THYRATRON FIRED IT'S POSITIVE HALF CYCLE
THIS THYRATRON ANODE IS NEGATIVE DURING THIS HALF CYCLE
THIS THYRATRON HAS JUST FIRED ITS ANODE VOLTAGE IS NEGATIVE
DURING THIS INTERVAL THIS TUBE MUST BE PREVENTED FROM FIRING AS ITS OUTPUT WOULD BE THAT OF A RECTIFIER
COUNTER EMF OF MOTOR ACTING AS GENERATOR DURING INVERSION
THIS TUBE MUST HAVE CONDUCTANCE OF A VALVE
FIRING POINT OF THE THYRATRON LYDAY LATE AS A RECTIFIER
CORRECTION FOR FIRING ANGLE

Figure 4. Graphic representation of discontinuous conduction rectification and inversion

maximum value. In series with the rectifier output is shown a large reactor with sufficient inductance to give continuous conduction. Above each diagram is shown graphically the transformer voltage, the average value of the rectifier output voltage, the generated voltage of the motor, and the average value of the *IR* (current resistance) drop of the circuit.

At *F* in Figure 2 the motor-armature connections have been reversed with the rectifier turned full on, that is, with the grid voltage in phase with the anode voltage. The current-limiting circuit of Figure 1 would soon phase back the grid voltage, but before this correction could take place a cycle or two of severe peak currents would ensue. At *G* the grid voltage of the thyratron has been phased back approximately 150 degrees, so that the tube does not "fire" or become con-

ductive until just before the transformer voltage connected to that anode goes negative. At the instant of firing, even though the transformer voltage is "nearing-zero-going negative," the net voltage on the tube is considerably positive because of the generated voltage of the motor. As soon as the thyratron is made conductive, this net positive voltage is applied across the reactance and the resistance in the circuit.

The distribution of the various electromotive forces and voltage drops is pictured more clearly in Figure 3, for both rectification and inversion. In this graphic representation of the voltages the armature reactance and the series reactor drops are lumped together as one IX_L drop. Likewise, the armature and circuit resistances are lumped and greatly exaggerated in this diagram. The effect of tube drop is neglected.

The positive voltage across the reactance and resistance starts the current building up through the armature circuit. During the current build-up, energy is supplied to the reactance by the transformer voltage until this voltage reaches zero and by the generated voltage of the motor. As the transformer voltage drops from its initial value, the rate of current rise becomes less, until, when the transformer voltage becomes more negative than the difference between the generated voltage and the IR drop, the current begins to decay. During the decay of current and flux, all of the energy which was supplied to the reactance during the current build-up is returned to the transformer by an induced voltage which, added to the difference between the generated voltage and the IR drop, keeps the current flowing against the negative voltage of the transformer. The average voltage across the inverter then is the difference between the generated voltage and the average value of the IR drop, as indicated in Figure 2.

Stated differently, the average terminal voltage of the tube circuit is the average voltage of the transformer over the period in which the tubes are conducting current. If the tubes are fired early in the positive half cycle, the average transformer voltage during conduction is positive; so the average output voltage is positive. If the tubes are fired at the end of the positive half cycle with no other electromotive force in the circuit to cause current to flow, the average voltage output is zero. However, if there is another electromotive force in the circuit of the proper polarity to cause the tubes to conduct current against the opposing negative voltage of the transformer, the average terminal voltage of the tube circuit is negative.

Shifting the firing point changes the period of the a-c cycle over which the tubes are conducting and thus changes the average transformer voltage opposing or aiding the flow of current. When the average transformer voltage made effective by firing the thyratron is aiding the flow of current, the circuit is supplying power to the motor. When the transformer voltage is opposing the current flow caused by the generated voltage of the motor, the circuit is inverting power from the motor to the a-c system.

Retarding the firing point makes the average tube-circuit counter voltage more negative and, with a given generated voltage, decreases the average current. As the current is decreased with a given reactance in the circuit, the energy transfer in the reactance may be insufficient to maintain current over a full half cycle, so the current becomes discontinuous, as in Figures 4 and 5. If the tube firing can be retarded to the point where the transformer voltage becomes more negative than the generated voltage, there will be no current conduction.

Perhaps a better picture of the relation of continuous and discontinuous conduction is obtained by a consideration of the current and voltage components. The firing of the tubes controls the portion of the transformer voltage wave which is effective in the circuit. This voltage consists of an average component plus multiple-frequency ripple voltages, the chief of which is at twice line frequency for a biphase circuit. The average current in the circuit is determined by the difference between the average effective transformer voltage and the generated voltage of the motor. The ripple current is determined by the reactance of the circuit. If the average value of current is greater than the negative peak of the ripple current, conduction is continuous. If the negative peak of the ripple current is greater than the average, the current becomes discontinuous, since the negative peak cannot reverse the current through the tubes. The transformer voltage then becomes ineffective until the next tube is fired. The value of the circuit reactance then determines the ratio of peak-to-average current and the conduction angle of the tubes.

With reference again to Figure 2, since the circuit is now taking energy from the motor instead of supplying it, the motor slows down, and the generated voltage drops. The grid voltage of the thyratrons is advanced to fire earlier in the cycle as at H in order to keep the average negative voltage of the inverter less than the motor. As the firing point advances to an angle corresponding to the peak of the transformer voltage, the average tube-circuit terminal voltage becomes zero. Advancing beyond this point gives a positive average voltage, and the tube circuit, operating as a rectifier, supplies power to the motor.

The diagrams in Figure 2 demonstrate the fact that, to get current flow through the circuit, the average terminal voltage of the tube circuit must be less negative (or more positive) than the generated motor voltage. Then, to increase the current the firing point is advanced, and to decrease the current the firing point is retarded, both for inverter and rectifier operation.

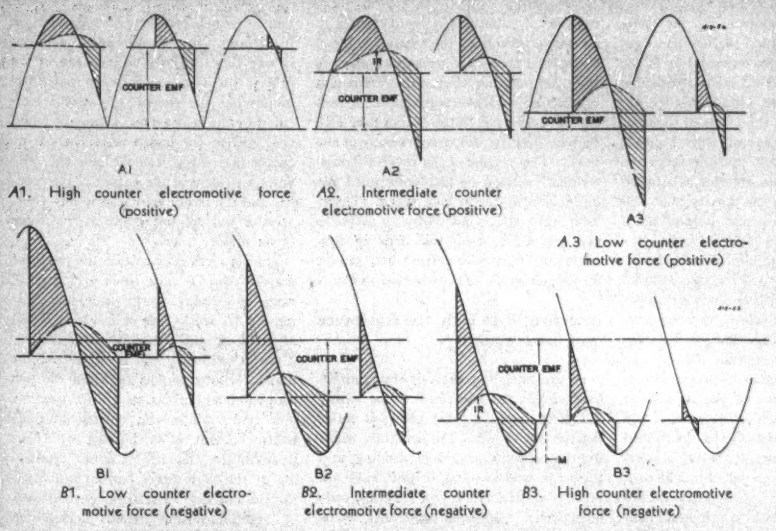
Current Control

The current-limiting circuit of Figure 1, consisting of the current transformer, its rectifier, and tube E, measures the anode current and operates in the proper sense to control the firing point of the thyratrons during the inversion period as well as during rectifier operation. When the rectified voltage from the current transformer becomes equal to the 75 volts of the voltage-regulator tube B, tube E begins to function, unsaturating the reactor in the phase-shifting circuit and so phasing back the grid voltage of the thyratrons. Phasing back the firing point increases the average negative voltage which decreases the current until a balance is reached. This circuit then regulates the firing point during both inverter and rectifier operation to hold the current constant.

Preconditioning to Prevent Plugging

If the process initiating a reversal is so controlled that the forward contacts of the reversing switch are opened, but the reverse contacts not closed until after the grid voltage has been phase-retarded to the proper angle, the severe current peaks of plugging can be avoided. This operation will be referred to as preconditioning for a reversal.

During the interval when the reversing switch is completely open, with the motor armature disconnected from the circuit, the only load across the rectifier circuit is a high-resistance circuit. Because a resistor will not keep current flowing in the circuit after the anode transformer voltage goes negative, if the thyratrons are fired anywhere in the positive half cycle, the average output voltage is



A1. High counter electromotive force (positive)

A2. Intermediate counter electromotive force (positive)

A3 Low counter electromotive force (positive)

B1. Low counter electromotive force (negative)

B2. Intermediate counter electromotive force (negative)

B3. High counter electromotive force (negative)

Figure 5. Effect of firing point and counter electromotive force on magnitude of anode current

A. Rectification—discontinuous currents

B. Inversion—discontinuous currents

M — Margin by which anode current does not become continuous and thereby tend to carry over into the region of rectification if not commutated out

positive and bears a definite relationship to the firing angle. Therefore, the positive voltage across the resistor load can be used as a measure of the firing angle. This relationship is utilized in the circuit of Figure 1 where the grid circuit of tube *E* is connected through a normally closed interlock, each on the forward and reverse contactors in series, to a tap on a resistance divider connected between a point 150 volts positive above neutral (point 5) and the positive side of the rectifier output (point 24). This serves to regulate the output voltage of the rectifier to a value which depends upon the ratio of the two sides of the resistance divider. By regulating to a low average voltage, the firing point of the thyratrons can be established at some point, such as in Figure 2G, which will give, upon closing the reverse contactor, the proper average negative voltage to limit the current to less than the current-limit value. A capacitor in the grid circuit of tube *E* "remembers" this conditioning signal momentarily, while the reverse contacts are closing, and the current is being established in the armature circuit. As this conditioning signal discharges from the grid capacitor the firing point is permitted to advance, increasing the current until the current signal takes over on tube *E*, which from there on limits the advance of the firing point to hold the current constant.

Where very fast forward and reverse contactors are used, it may be necessary to add a delay of a few cycles between the opening of the forward contacts and the closing of the reverse contacts to permit the conditioning circuit to retard the grid-voltage phase. This is accomplished by using a small d-c relay operating on the time constant of a capacitor and resistor, as *CR*1 in Figure 1.

Commutation During Inversion

In Figure 3 is indicated graphically the process of commutation in the tube circuit, for both rectification and inversion. The commutation of the current from one tube to another depends on the instantaneous voltage and the commutating reactance of the anode transformer. The greater that voltage, the faster the current can build up in the incoming tube and go out in the offgoing tube through the commutating reactance of the transformer. Commutation can take place only on a tube of more positive-anode potential.

In the case of rectification, commutation is not difficult, because it is initiated in the period when the incoming anode is going positive, or the commutating voltage is increasing. In the case of inversion, commutation of the tube currents can become troublesome, because it is initiated in the period when the commutating voltage is decreasing. If it is initiated early enough in the cycle there is sufficient voltage to commutate the current, but if the firing is retarded to very near the end of the cycle where there is little voltage the "should-be-offgoing" tube's anode may start going more positive than the "should-be-incoming" anode before commutation is complete. In that event the "should-be-offgoing" tube would take all the current again and conduct over the positive half cycle as well as the negative. This means that, while operating the biphase inverter at continuous current, the maximum retard of the firing point must be less than 180 degrees.

Maximum Voltage That Can Be Inverted

In a typical application of thyratron control to a 230-volt d-c motor, the maximum-armature speed-control setting is adjusted to give a speed corresponding to a counter electromotive force of 230 volts at full field. If then the anode transformer is designed to give an average output voltage of 280 volts, after allowing for tube drop, about 30 to 35 volts are left for *IR* compensation to hold the counter electromotive force and speed constant as the load is increased. If operated under this condition, the maximum-base-speed generated voltage that will be encountered will be 230 volts.

By comparison with rectifier operation it can be stated that, if the firing point could be retarded a full 180 degrees or to the zero voltage point and still effect commutation, with continuous conduction the negative voltage that could be developed would be equal in magnitude to the "full-on" rectifier voltage. A study of Figures 3 and 4 will show that tube drop subtracts from the rectifier voltage and adds to the negative inverter voltage

which can be developed. If the firing point is to be retarded slightly less than 180 degrees to insure commutation of the current from tube to tube, it is reasonable to expect a negative voltage slightly less in magnitude than the "full-on" rectifier voltage. The results of tests indicate that the maximum possible negative voltage for a biphase inverter is between 260 and 270 volts on the basis of 280 volts maximum average output as a rectifier.

Since the maximum-negative generated voltage that will be encountered will be 230 volts, with the motor running at base speed or below, the negative motor-terminal voltage developed during inversion will be less than this by the amount of the armature *IR* drop. Therefore, the firing point of the thyratrons normally will be well in advance of the zone which would involve commutation difficulties. Moreover, if the firing point is retarded to an angle which might produce trouble with commutation, the inverter voltage with continuous conduction would be more negative than the generated voltage. In that event, the current will be discontinuous, and it will not be necessary to commutate the current from tube to tube. This holds true only if the motor-terminal voltage is limited to about 230 volts which is the case for operation up to base speed of the motor.

Reversing From Field-Weakened Speeds

When the motor is to be operated at speeds above the base speed, the field is weakened by reducing the voltage of the field rectifier. The armature voltage is held the same as at base speed, 230 volts counter electromotive force plus the *IR* compensating volts. To fulfill the condition established previously, that the generated voltage does not exceed the base-speed voltage, the build-up of the field must be controlled during inversion. To obtain the maximum decelerating torque, however, the field should be strengthened at such a rate as to hold the generated voltage constant at the base-speed value.

The normal operation of the current signal on the field control is to strengthen the field at the limiting current. On attempting to invert at the same current limit, this control would raise the generated voltage beyond all control of the inverter. In the circuit of Figure 1 this voltage increase is prevented by tube *HH* and the heavy dotted circuit connected to it. The divider to which the cathode of tube *HH* is connected is so proportioned that, if the average value of the voltage across the armature goes more than 200 volts negative, tube *HH* begins conducting and overpowers the current signal of tube *EE* to the grid of tube *DD*, thereby limiting the strengthening of the field. This regulates the reverse motor-terminal voltage to 200 volts until the motor decelerates to base speed. Thereafter, tube *HH* is cut off by its cathodes going positive, and the field is controlled by the regular current-limit circuit for the remainder of the reversal period.

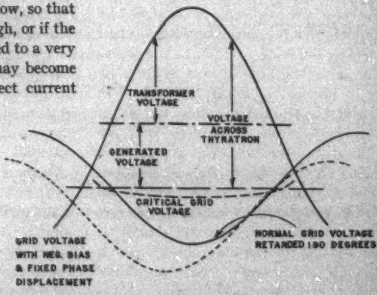
Inversion With Only the Reactance of the Armature

In the foregoing analysis the rectifier-load circuit was assumed to be highly inductive, and in some places a series reactor was shown. The armature winding, the commutating field winding, and the series field winding, if used, have appreciable inductance. A typical one-horsepower 1,150-rpm 230-volt motor was found to have an inductance ranging from 0.15 henry to 0.05 henry, depending on the degree of saturation of the iron structure. This range of inductance at the 120-cycle ripple frequency of the biphase circuit is sufficient to give continuous conduction at weak field and 100 per cent current but discontinuous conduction at full field and the same current. Other motors operated from this type of thyratron rectifier operating at from 100 to 150 per cent rated current vary from near continuous to continuous conduction.

As was pointed out before, if the reactance of the circuit is fairly low, so that the peak ripple currents are high, or if the average direct current is limited to a very low value, the peak current may become greater than the average direct current and so give discontinuous conduction, as in Figure 4; that is, the current goes out in one tube before it is initiated in the other. The voltage across the motor terminals has the general wave form indicated by the heavy line. It may be noted that, during the period when there is no conduction through the tubes, the only voltage evident at the output of the rectifier and the motor terminals is the generated or the counter electromotive force of the motor.

During rectifier operation the pulses of current may be quite short over the full range of voltage at light loads, lengthening out to nearly full, or full conduction at rated current, especially at weak field, if not at full field. The inverter operates normally between full load and 150 per cent full-load current, except for the first few cycles while the current-limiting-control circuit is advancing the firing point to give the current limit. Operating at the high direct current and with the inductance ordinarily encountered in fractional and small horsepower motors, the conduction angle of the tubes in a biphase system varies from about 135 degrees to a full 180 degrees. For the larger motors with less inductance, polyphase circuits, which have lower ripple voltages, are used; hence, the conduction angle is at or near $2\pi/P$ radians.

Although ordinarily operated at high current, the circuit will invert properly with the negative generated voltage at not more than 230 volts, at an average current well below the rated motor current, from one half to one fourth, by re-


TRANSFORMER VOLTAGE
VOLTAGE ACROSS THYRATRON
GENERATED VOLTAGE
CRITICAL GRID VOLTAGE
GRID VOLTAGE WITH NEG. BIAS & FIXED PHASE DISPLACEMENT
NORMAL GRID VOLTAGE RETARDED 180 DEGREES

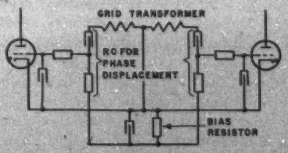


Figure 6. Alteration of grid voltage to permit firing late in the cycle

tarding the firing point to near 180 degrees. This means that on a reversal, if the pre-conditioning circuit retards the firing point to near 180 degrees while the contactors are open, the motor current upon closing the reverse contactor will be discontinuous current, as indicated in Figures 4 and 5, with an average value well below the rated value of the motor. After a cycle or two the current-limiting control will advance the firing point decreasing the opposing voltage of the inverter and increasing the average current to the limiting value. At this value it may still be slightly discontinuous or it may be continuous, as in Figure 3.

Discontinuous Operation With the Firing Retarded 180 Degrees

With discontinuous conduction there is not the commutation problem with late firing that is present with continuous conduction, since the current in one tube goes out before the other tube is fired. There is one precaution, however, that should be observed in connection with retarding the firing point a full 180 degrees. With the generated voltage of the motor reversed for inversion, the addition of the generated voltage and the transformer voltage gives a voltage across the thyratron which is positive for more than a half cycle, as shown in Figure 6. If the grid voltage is negative for only a half cycle, it cannot be retarded a full 180 degrees without causing the thyratron to fire just before or at the beginning of the positive half cycle instead of at the end of the positive half cycle as was intended. To fire at the beginning of the positive half cycle would give an extremely high peak current.

This condition can be avoided by one of two means. The retard of the grid voltage during the conditioning period while the armature contactors are open can be regulated to limit the angle to a safe position a few degrees less than 180. This will still hold the current upon closing the reverse contactor to less than the limiting value, and the firing point will advance as the current-limit control takes over. Misfiring may be prevented also by altering the grid-voltage wave, so that it is negative for more than 180 degrees. In Figure 6 is shown one possible method of altering the grid voltage to permit retarding the firing a full 180 degrees. This alteration was accomplished by adding to the sine-wave voltage from the grid transformer a negative bias and displacing the phase forward to bring the firing point to the same point as with the original grid voltage. The negative bias is a self bias by grid rectification. The phase displacement is by means of a resistor and capacitor. This grid circuit is included in the circuit of Figure 1.

With a grid voltage of this characteristic the circuit which conditions the tube for a reversal can be made to shift the firing point to a maximum retard without regulating. This could be accomplished in the circuit of Figure 1 by using the *F* and *R* contacts, which now connect the grid of tube *E* to a resistor divider, to connect the same grid to the cathode of tube *E*. This would serve as a false overcurrent signal to tube *E*, possibly giving a faster conditioning.

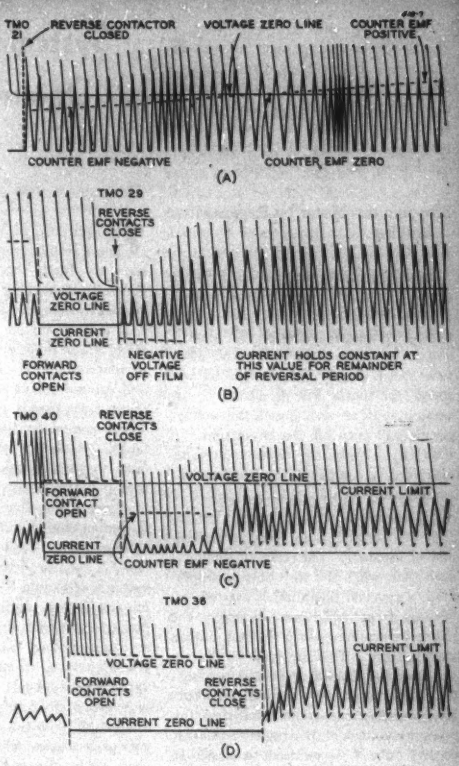


Figure 7. Oscillograms of actual reversing operation of electronic drive

Oscillograms of Actual Reversing Operation

In Figure 7 are shown tracings of the voltage across the armature terminals and the armature current at the beginning of a reversal. The film was hand operated, so it is slightly irregular along the time axis. Figure 7A does not include the opening of the forward contacts but does show one cycle of the preconditioned voltage. The preconditioning was adjusted to give a current at approximately the limiting value upon closing the reverse contactor. This oscillogram was taken with a one-horsepower motor with no connected load. The change of speed from fullforward to nearfull reverse can be followed by the trace of the generated voltage during the nonconducting period.

Figure 7B shows a full preconditioning period and the beginning of inversion. The firing was retarded by the preconditioning circuit to give a very low armature current upon closing the reverse contactor. This oscillogram was taken with a high inertia load on the motor, so that it slowed down very slightly in the time shown.

The oscillograms in Figures 7C and D were taken during a reversal from a field-weakened speed with a high-reactance motor. In Figure 7C, the current is dis-

continuous at the very low value on closing the reverse contacts but becomes continuous before the current limit is reached. Note that, while the current is discontinuous, the generated voltage shows up during the nonconducting period. In Figure 7D the current is continuous from the beginning.

Stopping the Motor by Regenerative Braking

Inversion can be utilized to bring the motor to a stop by regenerative braking. If, with the motor running at any speed, a normal reversal operation is started, and at the same time the reverse-direction speed control is switched to zero speed, the motor will decelerate by inversion, but at zero speed the voltage circuit will turn off the thyratrons. If then the switching devices are deenergized, a complete stop has been accomplished.

An example of a control circuit for this type of operation is included in the circuit of Figure 1. The relaying scheme is such that, when the stop button is operated, a reversal operation is started, reversing from whichever direction the motor was running when the stop button was pushed. This reversal is exactly the same as though it were initiated from either the forward or reverse push buttons, except that at the same time the reference voltage of the armature-voltage-control tube C is reduced to zero. It may be recalled from Figure 2 that during a normal reversal the voltage output of the rectifier at the instant of zero speed is not zero but is the IR drop of the motor. If the reference voltage of the armature-voltage-control tube is at zero, and if the IR compensating signal is still in operation, the rectifier will build up a positive voltage equal to the IR drop before the voltage-control tube takes hold. Since it requires no current to hold zero speed, the control quickly retards the firing point and, as the IR signal collapses, the rectifier voltage is reduced to zero. Turning the rectifier off deenergizes the Z relay, which in turn disconnects the other switching devices.

The deceleration is at constant horsepower during the field-control range of speed and at constant torque in the armature-control range right down to the last revolution.

Polyphase Circuits

Polyphase rectifier circuits may be made to invert in the same manner as the biphase circuit and with practically the same control circuit. There is one restriction for polyphase inversion that is not present for rectification. The grid voltage of the thyratrons for inversion must remain positive for an angle of not more than $2\pi/P$ radians where P is the number of phases.

In three- and four-phase circuits the inversion current can be limited to rated motor current or less by retarding the firing point a full 180 degrees. In six-phase circuits the firing point must be retarded more than 180 degrees beyond the beginning of the positive half cycle to limit the current properly.

In polyphase circuits, commutation at 180 degrees firing is not difficult with continuous current, since the voltages of adjacent phase do not go to zero at the same time.

System Voltages and Fault Currents Determined Easily on D-C Board

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THE purpose of this paper is to outline a simple procedure that may be used to obtain short-circuit data most generally needed for relay co-ordination studies by using a d-c calculating table.

A fairly complete relay co-ordination study can be made on systems using overcurrent and directional overcurrent phase and ground relays based on the three-phase short-circuit current and the residual current for single-phase-to-ground faults. However, where ground relays have to be co-ordinated with phase relays, it is desirable to know also the value of current that flows through phase relays when ground faults occur.

Since the development of distance relays, it is also desirable to know the voltages at various locations in the transmission system during three-phase and phase-to-ground faults. Where the zero-sequence voltage is used to polarize ground relays, it would often be advantageous to know the value of zero-sequence voltage in the system at a number of points for ground faults at various locations. Where relays are applied using negative-sequence currents and voltages, it may also be desirable to know those values during ground faults. All of these currents and voltages can be calculated by the method of symmetrical components; however, the calculations are quite lengthy and require considerable time. The same information can be obtained quickly and easily by the d-c calculating board and with relatively few and simple calculations. A description of the steps required is given in the next section. This is followed by a discussion of the factors involved and an analysis of the method.

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Description of Method

1. Set up the positive-sequence network on a convenient kilovolt-ampere base using reactances and impedances to give the desired accuracy.

2. Set up the zero-sequence reactances on one half the kilovolt-ampere base used for the positive-sequence network.

3. Take current readings for a three-phase fault at any point in the positive-sequence network. If possible use 100 volts on the board at all times. If it is not possible to use 100 volts, use whatever voltage that is convenient to represent 100 per cent voltage.

4. With a three-phase fault applied, read and record voltages on various busses of interest over the system by using a high-resistance voltmeter. The voltage measured from the three-phase fault to a particular bus in the positive-sequence network divided by the total board voltage and multiplied by 100 gives the per cent voltage on that bus. If the total board voltage is 100 volts, the voltmeter reading represents per cent voltage at the point being considered. Record this as V.

5. Apply a fault at a point in the zero-sequence network corresponding to that used for the three-phase fault in item 3, using the same voltage that was used for the three-phase fault. Read the total fault current and the distribution in the zero-

Reference

1. THYRATRON MOTOR CONTROL, E. E. Moyer, H. L. Palmer. AIEE TRANSACTIONS, volume 62, 1943, November section, pages 706-12.

sequence network on a scale having 3/2 as many divisions as the scale used for three-phase faults. These currents represent residual currents in the system and are the currents that will flow through ground relays for a phase-to-ground fault. If the 3/2 scale is not available, use the same scale that was used to read three-phase faults and multiply the results by 3/2 to give residual amperes.

6. While the phase-to-ground short circuit is still applied, use a high-resistance voltmeter and measure the voltage from the neutral bus (zero potential plane) in the zero-sequence network to the various busses of interest in the zero-sequence network. If a total board voltage of 100 volts is being used, the voltage read is the per cent zero-sequence voltage at the bus where the voltage is measured. If 100 volts is not used for the total board voltage, the reading divided by the total board voltage times 100 will give the per cent zero-sequence voltage. Record the voltage measured as V_0, a positive quantity.

7. With the phase-to-ground fault still applied, measure the voltage from the fault to the corresponding busses, in the positive-phase-sequence network, that were used to determine V_0. Record the voltage measured as V_{12}. The voltage V_{12} is the positive plus the negative-sequence voltage at the point where the voltage is measured in the positive-phase-sequence network. The reading will be in per cent if 100 volts is being used for a total board voltage. Otherwise, the reading over the total board voltage times 100 will give the per cent voltage.

8. The current which flows in the phase relays of the faulted phase during a ground fault may be calculated easily from data already taken by using the following relationship.*

$$I_{\phi 1}=\frac{I_G}{3}\left(2\frac{R_{P1}}{R_P}+\frac{R_{Q1}}{R_Q}\right)$$

9. The voltage at any point during a line-to-ground fault may be obtained from the following relationships. (Assume line A to be the faulted line.) The line-to-ground voltage expressed in per cent will be

$$E_A=V_{12}-V_0$$
$$E_B=-V_0-0.5V_{12}-J86.6$$
$$E_C=-V_0-0.5V_{12}+J86.6$$

where V_0 and V_{12} are expressed in per cent.

The line-to-line voltage expressed in per cent will be:

$$E_{AB}=E_B-E_A \qquad E_{CA}=E_A-E_C$$
$$E_{BC}=E_C-E_B$$

where all voltages are taken vectorially. Care must be taken where transformations are involved to consider the phase-angle displacement of each of the component voltages before combining them vectorially.

10. The positive- or negative-sequence component of voltage at any point during a ground fault may be obtained from the voltage readings already recorded as

$$V_2=\frac{E_G-V_{12}}{2}$$

If

$$E_G=100$$

then

$$V_2=\frac{100-V_{12}}{2}$$

$$V_1=V_{12}+V_2$$

where V_{12} and V_2 are both considered as positive quantities. The sequence components of currents in any branch of the circuit during a ground fault may be obtained from the following relationships:

$$I_1=I_2=\frac{I_G}{3}\times\frac{R_{P1}}{R_P} \qquad I_0=\frac{I_G}{3}\times\frac{R_{Q1}}{R_Q}$$

(I_2 and V_2 may be of interest where negative-sequence ground relays are being applied.)

Using Reactance or Impedance

When voltages are to be determined for use in determining distance relay performance, consideration should be given to whether reactance or impedance values are to be used in setting up the networks. If the ratio of reactance to resistance is fairly high, the result obtained will be sufficiently accurate if reactance is used. If the resistance is an appreciable part of the total impedance, a more accurate result may be obtained by using impedance rather than reactance. The particular system under consideration should be studied and the various constants compared to decide wisely on whether impedance or reactance should be used. It may be that in part of the network reactance values should be used and in other parts impedance values would give better results.

In the zero-sequence network it will be found usually that the ratio of X/R is high enough that reactance only may be used throughout with little error. However, for a high-resistance grounded system this, of course, would not be the case.

Choosing a Base

After the proper constants have been determined for the positive- and zero-sequence networks, a base should be chosen so as to utilize the rheostats available without having to put too many in series for a given line section nor too many in parallel for other lines, transformers, or generators. Due consideration also must be given to the range of the galvanometer readings and accuracy to which resistor settings can be made. It should be kept in mind that low-scale deflections on the galvanometer have not only a sizeable per cent error due to the observation but also an appreciable error due to the accuracy of the galvanometer, which has a guaranteed accuracy in a certain per cent of full scale.

Networks Needed

It is desirable to set up as few networks as possible and still obtain the desired information. Since the positive- and negative-sequence networks are very similar, little error results in most short-circuit studies by considering the two networks to be identical and setting them up as one network. The zero-sequence network is also necessary for ground-fault studies. Set up the positive-sequence network on the desired base and set up the zero-sequence network on a base one-half the size of that used for the positive-sequence network. These two networks are all that is required to give quite a complete study of currents and voltages for three-phase and phase-to-ground faults.

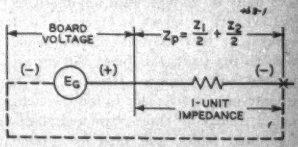


Figure 1. Three-phase fault with unit voltage and unit impedance

Unit current or base kilovolt-amperes flow to the fault

Three-Phase Faults

Consider the two networks in their most simple form as shown in Figures 1 and 2 on a per unit base. For clarification consider

$Z_1=Z_2=Z_0=$ unit impedance

Let

$Z_{1/2}+Z_{2/2}=Z_P$

For a three-phase fault, if one unit of voltage is impressed on one unit of impedance, one unit of current flows, which means that base kilovolt-ampere is flowing to the fault. Therefore, the network in Figure 1 may be used to determine three-phase faults.

Phase-to-Ground Fault

Consider a simple system having unit positive-, negative-, and zero-sequence impedances. Such a system has unit three-phase fault current and unit ground-fault current. If the zero-sequence impedance is set up on one-half the base

* See definition of symbols at the end of the paper.

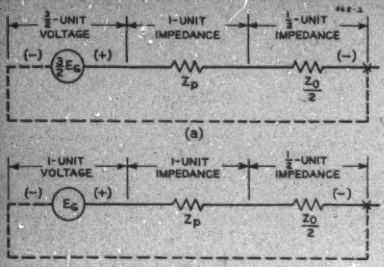


Figure 2. Phase-to-ground fault

(a). (3/2) unit voltage applied

$$I = \frac{(3/2)E_g}{(3/2)Z} = \frac{E_g}{Z}$$

Therefore, unit current or base kilovolt-amperes flow to the fault

(b). One-unit voltage applied

$$I = \frac{E_g}{(3/2)Z} = \frac{2}{3}\frac{E_g}{Z}$$

Therefore, two thirds of unit current or of base kilovolt-amperes flows to the fault

used for the positive-sequence network, as shown in Figure 2, then there exists 3/2 units of impedance to the fault. If 3/2 units of voltage were impressed on the network as shown in Figure 2a, unit current or base kilovolt-amperes would flow to the fault, this being the correct ground-fault current. However, it is usually more convenient to use the same board voltage for three-phase and phase-to-ground faults, and then for ground faults multiply the current readings by 3/2 or use a second scale on the galvanometer calibrated to read 50 per cent higher than the first. This second scale then reads the correct residual current, that is, the current which flows through ground relays operating on residual currents. The distribution of currents read in the zero-sequence network is the true distribution of residual current in the various branches of the network under consideration. This is apparent from the following consideration of Figures 3a and 3b.

In each figure consider $Z_1 = Z_2 = Z_0 = Z$ for simplification.

In Figure 3a, if unit voltage is impressed on 3 units of impedance 1/3 unit current flows. This in the ordinary consideration of symmetrical components is called

$$I_1 = I_2 = I_0 = I_G/3$$

where I_G is the residual current.

$$\frac{I_g}{3} = \frac{E_g}{Z_1 + Z_2 + Z_0} = \frac{E_g}{3Z}$$

or

$$I_G = \frac{3E_g}{3Z} = \frac{E_g}{Z} = \text{unit current} \qquad (1)$$

Figure 3b is the same fundamentally as that shown in Figure 2b, and if unit voltage is impressed on 3/2 units of impedance, 2/3 units of current flows, that is

$$\frac{E_g}{\frac{Z_1}{2} + \frac{Z_2}{2} + \frac{Z_0}{2}} = \frac{E_g}{(3/2)Z} = (2/3)\frac{E_g}{Z} \qquad (2)$$

If a multiplier of 3/2 is used or a 3/2 scale used as described previously then

$(3/2) \times (2/3)\frac{E_g}{Z} = \frac{E_g}{Z} = I_G$, the residual current

Therefore, the current determined by using the 3/2 multiplier or as read on the 3/2 scale in the networks shown in Figure 2b or 3b is residual current.

Voltage During Three-Phase Faults

The voltage at any point in a network during a fault is the vector sum of the voltages at that point in each of the sequence networks. The voltage at any point for a three-phase fault is the generated voltage minus the IZ drop to the point being considered, or the IZ drop from the fault to the point under consideration. Since no zero- or negative-sequence currents flow during a three-phase fault, only the positive-sequence network need be considered

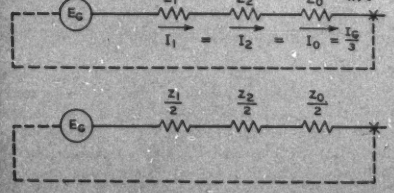


Figure 3. Residual current read directly for phase-to-ground faults

(a—above). Network with actual impedances (b—below). Network with impedances as set on calculating table

for voltage at any point. If the voltage is measured from the fault to the point where the voltage is desired in the positive-sequence network, when a three-phase fault is applied; the value obtained is proportional to the line-to-neutral voltage at that location. The measured voltage divided by the d-c board voltage times 100 is the per cent of the system voltage that exists at the point under consideration. If the d-c board voltage is 100, the voltmeter reads per cent voltage. This is shown in Figure 4.

Voltages During a Phase-to-Ground Fault

When a phase-to-ground fault occurs on a grounded system, positive-, negative-, and zero-sequence currents flow, and the voltage at any point is the vector sum of the positive-, negative-, and zero-sequence voltages at that point. Each of the sequence voltages is produced by its particular sequence current flowing

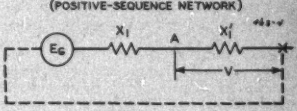


Figure 4. Voltage during a three-phase fault

The per cent voltage at point A is $(V/E_g)100$. If $E_g = 100$ volts, then V is the per cent voltage at A

through that sequence impedance. The voltage in each network at a given point is the generated voltage in that network minus the IZ drop to the point being considered. Since the positive-sequence network is the only one having a generated voltage, the expressions for the sequence voltages at a given point, L, are

$$_LE_1 = E_G - I_1Z_1 \qquad (3)$$

$$_LE_2 = 0 - I_2Z_2 \qquad (4)$$

$$_LE_0 = 0 - I_0Z_0 \qquad (5)$$

The phase-to-neutral voltage on the faulted phase, say A, at the point L is

$$_LE_A = {}_LE_0 + {}_LE_1 + {}_LE_2$$

From symmetrical components the voltages to neutral on the two unfaulted phases are

$$_LE_B = {}_LE - 0.5({}_LE_1 + {}_LE_2) - J0.866({}_LE_1 - {}_LE_2)$$

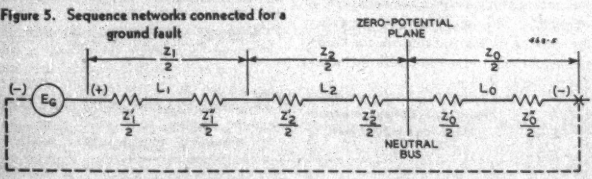
$$_LE_C = {}_LE_0 - 0.5({}_LE_1 + {}_LE_2) + J0.866({}_LE_1 - {}_LE_2)$$

As indicated by equations 3, 4, and 5, $_LE_1$ is positive and $_LE_2$ and $_LE_0$ are negative for the phase-to-ground fault condition

in which I_3 and I_0 are in the same direction as I_1. In the following material, therefore, the E's are used to include the significance or relative direction, whereas V's are all positive numbers and must be used with appropriate signs. Thus ${}_LE_1 = {}_LV_1$, and these are used interchangeably. However, ${}_LE_2 = -{}_LV_2$, and ${}_LE_0 = -{}_LV_0$. The E's are actually vectors, although those obtained directly from the d-c board are all in phase or 180 degrees out of phase. Thus, it is consistent later to use the symbol E in expressions for vectorial voltages of the other phases.

It is often desirable to know the voltages at several locations during a phase-to-ground fault to predict the performance of voltage relays, distance relays, undervoltage devices, or the general system disturbance. It is also often desirable to know the zero-sequence voltage at a number of locations to determine the performance of directional ground relays using zero-sequence voltage for polarization.

Figure 5. Sequence networks connected for a ground fault



Zero-Sequence Voltage

From equation 5 above the zero-sequence voltage at the point L is the I_0Z_0 drop from the zero potential plane or neutral bus of the zero-sequence network to the point L. The current flowing in the zero-sequence network as set up in Figure 2b is $(2/3)I_G = 2\,I_0$. The impedance used in this network, however, is set up on one-half the normal base used for the positive-sequence network, and the value of zero-sequence impedance in the network on a per unit base is $Z_0/2$. If two times unit current flows through one-half unit impedance, unit voltage is produced or $2I_0Z_0/2 = I_0Z_0 = {}_LV_0$. Therefore, the voltage measured from the zero potential plane or neutral bus to point L in the zero-sequence network represents the zero-sequence voltage at the point L. If E_G is 100 volts, then $({}_LV_0/100)\ 100 = {}_LV_0$. Therefore, if $E_G = 100$, ${}_LV_0$ is the per cent zero-sequence voltage at point L. The per cent zero-sequence voltage, ${}_LV_0$, is the per cent of the maximum zero-sequence voltage which is the same as three times the normal line-to-neutral voltage.

Ground-Relay Voltage

If the secondary or relay zero-sequence voltage corresponding to 100 per cent primary zero-sequence voltage is known, the per cent zero-sequence voltage, ${}_LV_0$ divided by 100 and multiplied by this secondary voltage will give the zero-sequence volts on the ground relay. The most common method of obtaining polarizing voltage for ground relays is to use wye-wye main potential transformers, grounded on each side, and wye-broken-delta auxiliary potential transformers with the wye grounded. With this combination the polarizing voltage on the relay can be obtained readily for the condition of 33 per cent zero-sequence voltage. This condition is simulated when the primary of one main potential transformer is disconnected from the line and short circuited with the other two transformers energized from the two remaining lines of the three-phase source.

For example, suppose the phase-to-neutral voltage is 19,000 volts, and potential is supplied to the ground relay through three 300/1 ratio wye-wye main potential transformers connected to three 1/1.73 ratio wye-broken-delta auxiliary transformers. The relay voltage for the simulated 33 per cent zero-sequence voltage condition is then

$$(19{,}000/300)1.73 = 110 \text{ volts}$$

or 100 per cent zero-sequence voltage corresponds to 330 volts on the relay.

It may be found helpful to record this 100 per cent secondary zero-sequence voltage on the reactance diagram at all the points where the zero-sequence voltage is of interest for future reference, thus eliminating duplicate calculations.

Since various ratio auxiliary potential transformers are used often at different locations, the advantage of recording the maximum secondary zero-sequence voltage is apparent. $(V_0/100)$ 330 is the voltage on the ground relay in the aforementioned example. V_0 seldom exceeds 60 per cent for a solidly grounded system and is more often 33 per cent or less.

Positive- and Negative-Sequence Voltages

It will be shown first that the sum of positive- and negative-sequence voltages can be read directly from the calculating board. Figure 5 is an equivalent diagram of the network arrangement on the board with the point L identified in each network. Let E_G be unit voltage, and $Z_1 = Z_2 = Z_0 = 1$ unit of impedance.

Since unit voltage is impressed on a total of 3/2 units of impedance, 2/3 units of current flow, as was shown in Figure 2b. Since unit current is I_G, the current that flows is $2/3\ I_G = 2I_0 = 2I_1 = 2I_2$.

The positive- and negative-sequence impedances being identical may be combined as shown in Figure 6, the current being the same as in Figure 5. The positive- and negative-sequence voltages during a ground fault at point L of Figure 6 are shown in Figure 7. They are derived as follows from Figures 5 and 6:

$${}_LE_1 = E_G - \frac{2I_1Z_1'}{2}$$

$${}_LE_2 = 0 - \frac{2I_1Z_1'}{2}$$

$${}_LE_1 + {}_LE_2 = E_G - \frac{2I_1Z_1'}{2} - \frac{2I_1Z_1'}{2} = E_G - 2I_1Z_1'$$

Let

$$E_G - 2I_1Z_1' = {}_LV_{12}$$

$${}_LV_{12} = {}_LE_1 + {}_LE_2$$

Note that ${}_LV_{12}$ is the voltage that exists between the fault on the board setup and the point L in the positive-sequence network when a ground fault exists. If E_G is 100, ${}_LV_{12}$ is in per cent.

From equation 4 the negative-sequence voltage at point L is

$${}_LE_2 = -I_2Z_2'$$

Since Z_2' is assumed equal to Z_1' and $I_2 = I_1$, and if it is noted from Figure 7 that

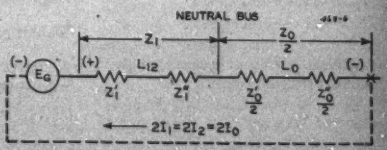


Figure 6. Sequence networks connected for a ground fault with positive- and negative-sequence networks combined

$I_1Z_1' = (E_G - {}_LV_{12})/2$, therefore

${}_LE_2 = -I_2Z_1' = -(E_G - {}_LV_{12})/2$

or the numerical value of negative-sequence voltage is

${}_LV_2 = (E_G - {}_LV_{12})/2$

It is in per cent if $E_G = 100$.

The positive-sequence voltage at point L is

${}_LE_1 = {}_LV_{12} - {}_LE_2$

since ${}_LV_{12}$ is equal to ${}_LE_1 + {}_LE_2$. However, E_2 is negative and has the magnitude ${}_LV_2$. Thus

${}_LV_1 = {}_LE_1 = {}_LV_{12} + {}_LV_2$

Phase-to-Ground Voltages

The expressions for line-to-ground voltages in terms of board measurements may be derived as follows. The per cent phase-to-ground voltage on the faulted phase, say A, at point L is

$E_A = {}_LE_1 + {}_LE_2 + {}_LE_0 = {}_LV_{12} - {}_LV$ (since ${}_LE_0$ is negative)

From symmetrical components

${}_LE_B = {}_LE_0 - 0.5({}_LE_1 + {}_LE_2) - J0.866({}_LE_1 - {}_LE_2)$

${}_LE_C = {}_LE_0 - 0.5({}_LE_1 + {}_LE_2) + J0.866({}_LE_1 - {}_LE_2)$

$({}_LE_1 + {}_LE_2) = V_{12}$

${}_LE_1 - {}_LE_2 = (E_G - I_1Z_1') - (0 - I_2Z_2')$

${}_LE_1 - {}_LE_2 = E_G$

${}_LE_B = -{}_LV_0 - 0.5V_{12} - J0.866E_G$

${}_LE_C = -{}_LV_0 - 0.5V_{12} + J0.866E_G$

As stated previously, ${}_LV_0$ and V_{12} both are considered as positive numbers. If $E_G = 100$, the phase-to-ground voltages at point L become

${}_LE_A = V_{12} - {}_LV_0$

${}_LE_B = -{}_LV_0 - 0.5V_{12} - J86.6$

${}_LE_C = -{}_LV_0 - 0.5V_{12} + J86.6$

All values will be in per cent of phase-to-neutral voltage at point L.

Line-to-Line Voltages

The line-to-line voltages in per cent of line-to-neutral voltage will be

${}_LE_{AB} = {}_LE_B - {}_LE_A$ taken vectorially

${}_LE_{BC} = {}_LE_C - {}_LE_B$ taken vectorially

${}_LE_{CA} = {}_LE_A - {}_LE_C$ taken vectorially

Conclusion

A complete picture of currents and voltages may be determined with sufficient accuracy for most relaying problems in a system during short circuits by using a d-c calculating board with very little more time and effort than is normally used to measure currents for three-phase and phase-to-ground faults. Only one setup, using two simple networks, is required. The only readings necessary are current or kilovolt-ampere for three-phase and line-to-ground faults, including the current distribution of each desired, and V, V_{12}, V_0, for each fault condition at as many points as the voltage may be of interest.

Other values of voltages and current such as V_1, V_2, V_A, V_B, V_C, I_1, I_2, I_0, I_ϕ may be obtained by very simple calculations by using the currents and voltages that were measured. The voltage calculations are simplified by using a total board voltage of 100 volts, so that the voltmeter reads directly in per cent. The same result may be obtained where a board voltage other than 100 must be used by preparing a special scale for the high-resistance voltmeter which is marked in per cent of full board voltage, or by converting the readings taken into per cent of full board voltage.

Thus, a complete analysis of performance for modern relays may be made quickly and with sufficient accuracy for both three-phase and phase-to-ground faults by using the d-c calculating board and a high-resistance voltmeter.

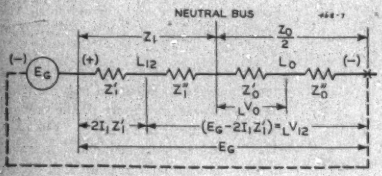


Figure 7. Voltage measurements for a ground fault

Definitions of Symbols Used

I_G = total residual amperes flowing to a ground fault

$I_{\phi 1}$ = current flowing through phase relays in branch 1 for a ground fault

I_1 = positive-sequence component of current

I_2 = negative-sequence component of current

I_0 = zero-sequence component of current

Z_1 = positive-sequence impedance

Z_2 = negative-sequence impedance

Z_0 = zero-sequence impedance

R_P = reading for total three-phase fault

R_{P1} = reading for branch 1 for a three-phase fault

R_G = reading for total ground fault

R_{G1} = reading in branch 1 for a ground fault

(Note that kilovolt-amperes or amperes may be substituted for R_P, R_{P1}, R_G, R_{G1} if more convenient.)

E_G = unit voltage or 100 per cent voltage on the d-c board

V = voltage measured from the fault to some point where the voltage is desired in the positive-sequence network when a three-phase fault is applied

V_{12} = voltage measured on the board from the fault to some point where the voltage is desired in the positive-sequence network when a phase-to-ground fault is applied

V_0 = voltage measured on the board from the neutral bus or zero-potential plane to some point where the zero-sequence voltage is desired in the zero-sequence network when a phase-to-ground fault is applied

${}_LV_0$ = voltage that exists on the board from the neutral bus to a point of interest in the zero-sequence network designated as L

(Note that the subletter L is also used to designate various other voltages which exist at point L.)

E_1 = positive-sequence component of voltage

E_2 = negative-sequence component of voltage

E_0 = zero-sequence component of voltage

E_A = the line-to-ground voltage on phase A

E_B = the line-to-ground voltage on phase B

E_C = the line-to-ground voltage on phase C

V with subscript designates absolute magnitude of the vector E with same subscript, namely, V_2 is magnitude of E_2.

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Corona in Aircraft Electric Systems as a Function of Altitude

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Synopsis: Corona-starting voltages of the components of a 208-volt 400-cycle grounded-neutral electric system are reported for conditions to simulate altitudes between sea level and 50,000 feet. The corona characteristics are shown to be functions of air pressure, electric-field geometry, humidity, and the cleanliness of insulating surfaces. The effect of reducing pressure is shown to lower the corona-starting voltages of aircraft cables by as much as 60 per cent because the dielectric strength of large air gaps drops a comparable amount. Reducing the pressure has small effect on the corona-starting voltages of low-voltage capacitors, because the dielectric strength of small air gaps is nearly independent of pressure. Moisture and dust on insulating surfaces and moisture in aircraft cables produce corona-like disturbances below 208 volts. Data are presented on cables, capacitors, parallel studs, and needle gaps. Under dry conditions all corona-starting voltages were well above the operating voltages of the system.

CORONA in an electric system consists of minute arcs which produce ozone and nitrous acid in air; they carbonize oil, paper, and cotton; they oxidize and age rubber, and they corrode metal. Corona at operating voltages has often caused the rapid deterioration of the electric equipment containing the corona. In addition, high-frequency radiation is produced which may interfere with radio and allied instruments. For these reasons engineers working in the design and development of electric equipment should know the voltage at which corona first appears in that equipment.

Corona in insulation usually consists of the breakdown of small air pockets and gaps. It is well known that at high altitudes the density and dielectric strength of air are reduced greatly from their sea-level values. The change from sea level to 50,000 feet causes the dielectric strength of a one-centimeter parallel-plane air gap to drop by more than 75 per cent. Because of this, the question has been raised as to whether corona-starting voltages would not also drop greatly at high altitudes. This paper is an attempt to answer that question in a manner to be helpful in general design. Emphasis is placed on the specific problem of determining whether or not corona will exist in the steady-state operation of a 208-volt 400-cycle electric system.

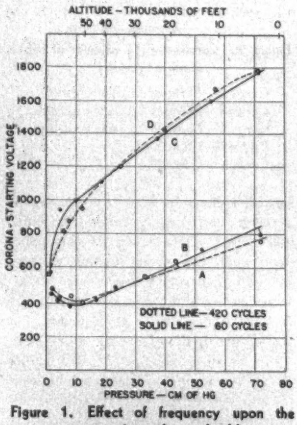

Figure 1. Effect of frequency upon the corona-starting voltage of cables

Curve *A*—Cable 1 at 420 cycles
Curve *B*—Cable 1 at 60 cycles
Curve *C*—Cable 4 at 60 cycles
Curve *D*—Cable 4 at 420 cycles

Corona measurements were made upon the following:

Aircraft cables	Figures 1, 2, 3, and 4 Table II
Capacitors	Figure 5, Table I
Meter-case back	Figures 6 and 7
Parallel studs	Figures 8 and 9
Needle gaps	Figure 10
Contaminated surfaces	Table III

Variables were pressure, humidity, voltage, and frequency.

At the close of the report, data are discussed which deal with the increase of the sparking potential of small gaps as the gap is made smaller. It is shown that this variation has great influence on the corona-starting voltage of capacitors at altitudes easily attained today.

All tests were made at room temperature and at an altitude of 1,000 feet. A method is given for correcting accurately the data on corona and breakdown in air to the low temperatures of high altitudes.

Method of Test

When corona occurs in any piece of equipment to which voltage is applied, the current to that piece of equipment includes high-frequency components. In many cases the high-frequency components can be separated from the normal charging currents, be amplified, and be viewed on the screen of a cathode-ray oscilloscope. With sufficient sensitivity at his control, an operator can thus detect the first pulses of corona and find the lowest voltage at which deterioration due to this cause can exist. A simple method for accomplishing these measurements has been described by G. E. Quinn.[1]

It is characteristic of this type of measurement that corona in a low-capacitance system, such as a needle gap, is much easier to detect than corona in a high-capacitance system. In the tests to be described in this report, the sensitivity was such that the first indication of corona was usually an off-scale deflection of the oscilloscope spot. The equipment was designed for more difficult high-capacitance work, and the results of that work check years of insulation experience. Because all of the tests in this paper were on low-capacitance samples, the writer feels that if there was any minute amount of undetected corona in the electric fields studied, it was negligible.

The tests were made with the samples in a desiccator which could be evacuated to two millimeters of mercury. Two diametrically opposite electric connections were brought into the desiccator and, when necessary, terminated in spheres. This insured that there would be no corona except in the test sample.

All tests were run at room temperature and, except when stated otherwise, with a drying agent in the desiccator. All tests were run at 60 cycles except those which were made to show that the frequency change from 400 to 60 cycles had small effect. When not stated otherwise, voltages are rms.

In this paper, corona is defined as ionization in a fluid dielectric without the breakdown of the sample in which the fluid is contained. Examples are numer-

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ous. Ionization may occur in air around metal points or in oil between transformer windings. If the test piece does not become a conductor from terminal to terminal, the ionization is defined as being corona. In air, oil, and other good dielectrics corona appears in a characteristic manner. The fluid suddenly ionizes at a certain voltage; at that voltage a large deflection of the oscilloscope spot can be seen.

In the tests involving moist samples the pulses detected were of a different type. The pulses, instead of first appearing with a large deflection, often grew from an indetectable first amplitude. This type of disturbance was also called corona because the moisture which caused the disturbance was part of the dielectric. It could not always be differentiated from ionization in air. The only tests which gave indications of ionization at voltages near 208 volts were tests with very moist samples.

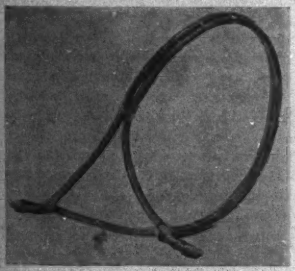

Figure 2. Form of cable-to-cable samples

The corona-starting and the breakdown curves are plotted against the pressures at which the tests were run. A second scale gives the altitudes which correspond to the test conditions insofar as corona or breakdown in *air* are concerned. As explained later in the paper the tests made at room temperature and at variable pressure have been corrected to high-altitude temperatures and pressures. The equivalent altitudes apply accurately when the ionization occurs in air, but they do not apply when the ionization occurs in a liquid such as in the moist cables. In the latter tests the equivalent conditions are doubly uncertain because the water will freeze at high altitudes unless the equipment is heated.

Frequency—Figure 1, Table I

The influence of frequency on corona in air which includes no solid barriers has been shown by Peek[2] to be negligible through the frequency range from 60 to 420 cycles. Data taken for this paper show that the corona-starting voltages of fields with solid barriers are not affected by more than ten per cent by the aforementioned change in frequency.

For example, Figure 1 shows the corona-starting voltages of two cables tested at varying pressure and at both 60 and 420 cycles. There is no significant difference between the curves at the two frequencies.

Three types of capacitors also were checked for the present paper (Table I). The values given depend as much on the capacitor construction as on the dielectric material.

The conclusion may be drawn from Table I that the change of frequency from 60 to 420 cycles produces a small effect upon corona-starting voltages.

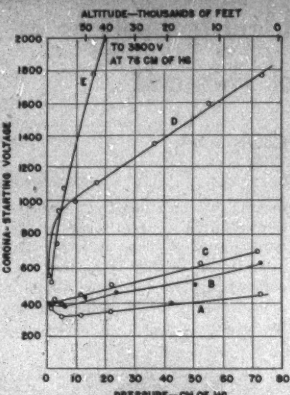

Figure 3. Corona-starting voltages of cables at room humidity

Curve *A*—Number 8 cable to cable
Curve *B*—Number 1/0 cable to cable
Curve *C*—Number 16 cable to cable
Curve *D*—Cable 4
Curve *E*—Cable 5

Cables—Figures 2, 3, 4, and Table II

Five types of cable* were tested.

1. Number 16 (19/0.0113) Deltabeston (Flamenol, asbestos, and cotton braid over tinned copper—single conductor).

2. Number 8 (7/24/0.010) Deltabeston (Flamenol and cotton braid over tinned copper—single conductor).

3. Number 1/0 (19/55/0.010) Deltabeston (Flamenol and cotton braid over tinned copper—single conductor).

4. Number 12 (19/0.018) Deltabeston (Flamenol and cotton braid over tinned copper—three conductors).

5. Number 16 (26/0.010) household appliance cord, 220-volt (rubber and cotton braid over bare copper—two conductors).

* Cable sizes given are American Wire Gauge numbers; the number of strands, the number of wires in each strand, and the diameter of each wire in inches are indicated in parentheses.

Cables 1, 2, and 3 were tested in two electric-field configurations. Cable-to-cable tests were made by binding together two equal lengths of cable (Figure 2). The two ends of each wire were connected to one of the connecting spheres. This was done to insure against corona from the free ends. Cable-to-ground tests were run by laying a single large loop of the cable on a metal plane.

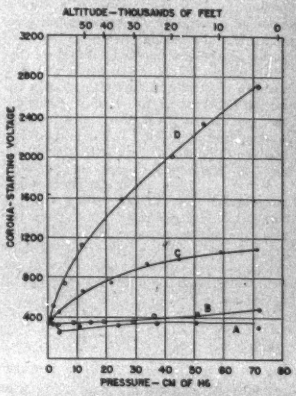

Figure 4. Effect of drying on the corona-starting voltages of number 8 cable

Curve *A*—Cable to ground, 98 per cent humidity for eight hours
Curve *B*—Cable to ground, room humidity
Curve *C*—Cable to ground, vacuum dried
Curve *D*—Cable to cable, vacuum dried

Cable 4 was a preconstructed cable with three insulated wires covered and bound together with an outer fiber wrapping. Two of the wires were connected together at one end and connected to the ground terminal of the corona detector. The third was placed at high potential. The three opposite ends were immersed in a small bottle of oil.

Cable 5 was the common 220-volt lamp and appliance cord.

Figure 3 shows cable-to-cable corona-starting voltages for cables with a moisture content as absorbed at room temperature and humidity. The term "room humidity" is not customarily used to describe the conditions of a test. However, under controlled humidities it took days for a cable to come to equilibrium. Wide variations in humidity

from day to day had small effect upon the corona-starting voltage. For reference, the average humidity for the three days in which the tests of Figure 3 were run was 76 per cent. The important points to notice are that corona never appeared below 300 volts and that the 220-volt lamp cord was decidedly superior to the airplane cables insofar as corona was concerned. The thicker insulation of the appliance cord was responsible for its high corona-starting voltage.

Figure 4 shows the effect of drying the number 8 cable by heating it under vacuum. The highest and the lowest curves on the graph were the extremes, the difference being a result of varying the moisture content from about zero to that absorbed in eight hours at 98 per cent humidity. The cables were stored and tested in desiccators, were kept dry by heat and a drying agent, or were kept at 98 per cent humidity by the presence of $CaSO_4$ and water.

The immersion in water of the number 8 cable-to-cable sample caused the corona-

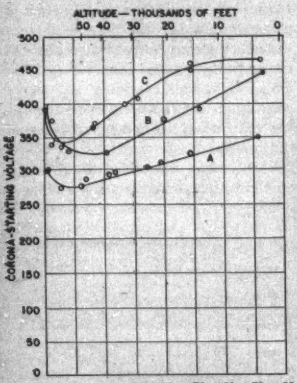

Figure 5. Corona-starting voltage of dry, nonhermetically sealed capacitors

Curve *A*—One-mil paper dielectric, not sealed or impregnated

Curve *B*—Two-mil paper dielectric, wax impregnated

Curve C—Two-mil paper dielectric, not sealed or impregnated

starting voltage to rise to 2,850 volts at 76 centimeters of mercury. This voltage was higher than the corresponding voltage on the dry-cable curve. It was seen that as the moisture content of the cables was increased the corona-starting voltages passed through a minimum. A few points on the curve, taken at room temperature and pressure, are shown in Table II.

Although it is probable that the 300-volt point is not the exact minimum, altitude and pressure have small effect. Therefore, if the cable has functioned satisfactorily at similar humidities at low altitudes, these tests indicate that it will continue to function satisfactorily at high altitudes. All cables showed similar variations with moisture content.

Figure 4 shows the number 8 cable-to-ground corona-starting voltages. It would be expected from a consideration of the electric field that the values would be half those obtained when two cables were bound together. This was roughly the case when the cables were dry (compare curves *D* and *C*, Figure 4). However, at room humidity both curves dropped to approximately the same values.

Capacitors—Figure 5 and Table I

A number of capacitors were tested at variable pressure. Typical data are shown by the three curves of Figure 5. Curves *A* and *C* were taken on capacitors which were prepared in a manner

Figure 6. Meter-case back, two-inch diameter

to include the most air voids possible. The paper was dry and not impregnated. The rolls were loosened to permit complete evacuation of the interior of the capacitor. Curve *B* was taken as a typical wax-impregnated sample. Upon the reduction of pressure, as the breakdown strength of large air gaps dropped by a factor of five the breakdown strength of the air voids (the corona-starting voltages of the capacitors) dropped by as little as 20 per cent. The reason for this action is given at the end of this paper in the section on the dielectric strength of air.

In order that the effect of moisture could be studied, four of the unimpregnated roll capacitors were dried for 48 hours under vacuum and at 105 degrees centigrade. No change in the corona-starting voltages could be found.

It appears that the operating voltages of low-voltage capacitors which are not hermetically sealed and which are to be used at high altitude will not have to be decreased by more than 30 per cent from sea-level operating voltages even if the capacitors contain large air voids.

Meter-Case Back—Figures 6 and 7

A circular meter-case back (Figure 6) supporting two connecting bolts was

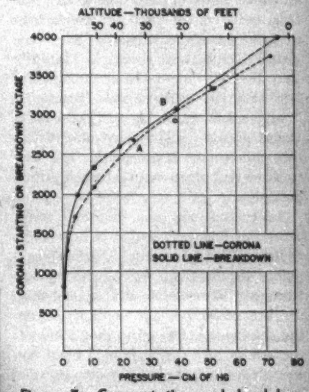

Figure 7. Corona-starting and breakdown voltage between bolts through the meter-case back of Figure 6

Curve *A*—Bolt heads not recessed

Curve *B*—Bolt heads recessed

also checked for corona. The bolts were mounted with an inch of separation between centers. In one test the heads and nuts were recessed; in the other they were mounted on plain surfaces. Because the curves for the two mounting methods are essentially the same, there is no advantage from the corona and the low-pressure arcover standpoint, in recessing the studs.

Toward the high-pressure end of the curve, the ionization did not occur along the surface of the base or through the air between the studs. This fact was ascertained by immersing the base and studs under oil after the data for Figure 7 had been taken. Under oil the same corona-starting voltage was found at room pressure as was found in air. In fact the same type of curve of corona-starting voltage versus pressure was traced down to about 30 centimeters of mercury. The ionization actually oc-

curred in air which was trapped in the space surrounding the studs where they passed through the insulation. At lower pressures the position of ionization shifted until breakdown appeared between the studs. Probably the point of this shift occurred at the knee of the curve.

Parallel Studs Through Plane Surfaces—Figures 8 and 9

Some additional data on studs through plane surfaces were taken. Number 4/40 studs were screwed into a one-half-inch insulating block (Figure 8). They extended one-half inch above the surface and were mounted perpendicularly in two spacings: one-fourth and three-eighths inch between threads. The leads were brought out under oil through the bottom of the insulated plate (Figure 8).

Figure 9 shows the curve of breakdown versus pressure. The only value of the corona-detection device in this test was to show that there was no corona before breakdown.

As corona was not involved, work along this line was thought to be outside of the scope of this report. Obvious weak points in the data were therefore not removed. For example, it was found that the breakdown voltage depended upon the sharpness of the edges at the top of the studs. The tip melting caused by one arcover with a 20,000-ohm resistor in series was sufficient to raise the breakdown voltage by 20 per cent. This effect probably is present in the data of Figure 9.

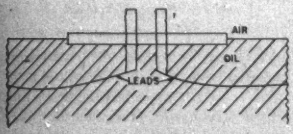

Figure 8. Parallel studs through insulating surfaces

The conclusion can be drawn that there will be no problem with *corona* on studs at practical spacings.

Needle Gaps—Figure 10

From the standpoint of corona, the worst electrode configuration that can exist is that of collinear needles facing point to point. For this reason number 8 needles at one-eighth-inch and one-fourth-inch spacing were checked for corona as a function of pressure. At high pressures corona occurred before breakdown; but, as shown on Figure 10, at low pressures

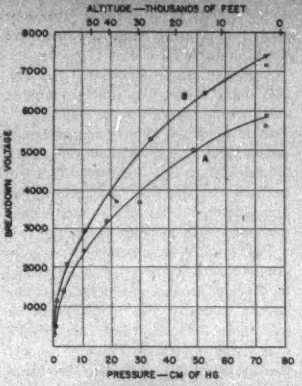

Figure 9. Breakdown voltage of the parallel studs of Figure 8

Curve *A*—One-fourth-inch spacing between threads

Curve *B*—Three-eighths-inch spacing between threads

breakdown occurred without first showing corona.

At high altitudes the random ionization is much greater than at sea level. To increase the number of ions in the test chamber, radium (1.8 micrograms) was placed four inches away from the gap. The effects of the radium were to reduce the time between pulses of corona, to reduce the short-time breakdown voltage of the gaps, and to make the breakdown and corona-starting voltage more exactly reproducible. All data were taken in one minute step-ups, the corona-starting voltages being defined as the voltage at which the first isolated pulses of corona occurred.

It may be concluded that at spacings above one-eighth inch no corona will be encountered in any electrode configuration at or near 208 volts.

Contamination of Surface Between Studs

Data were taken on the contamination of the plastic surfaces between the studs of Figure 8. The same conditions of test were used, care being taken to keep oil from the surface by cleaning with Solvatone. The object of this section of the work was to see if corona or high-frequency discharges could possibly be produced below 208 volts.

Data were taken with $^1/_{32}$ inch of dry dust lying on the surface. As in Figure 9, no corona appeared before breakdown, and the breakdown values were not lowered by the presence of the dust.

Table I. Corona-Starting Voltage of Capacitors at 420 Cycles as Per Cent of 60-Cycle Value

	60 Cycles (Per Cent)	420 Cycles (Per Cent)
Paper-Pyranol	100	95 to 90
Mica	100	91
Unimpregnated paper	100	105

The surface was then cleaned. An open pan of warm water was placed in the desiccator. The pressure was reduced to four centimeters of mercury where the water boiled freely, depositing a thick uneven layer of moisture on everything in the desiccator. High-frequency discharges appeared at from 500 to 700 volts as the pressure was varied from 2.4 to 74 centimeters of mercury. As the water evaporated from the surface, this discharge voltage rose to 1,700 volts at 74 centimeters.

At pressures above four centimeters, the steam soon cleared up. To produce vapor at all pressures, the principle of the Wilson cloud chamber was used. A small amount of tobacco smoke was blown into the desiccator to permit a cloud to appear as the pressure was reduced. Under these conditions the discharge voltage varied from 800 to 1,700 volts, at various pressures. No curve could be plotted because the pressure had less effect than did random changes in the moisture.

Finally, dust was added to the water on the surface, forming a mass of mud

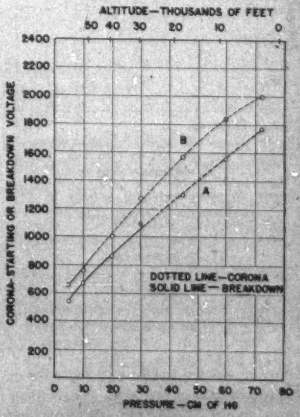

Figure 10. Corona-starting and breakdown voltage of needle gaps

Curve *A*—One-eighth-inch gap

Curve *B*—One-fourth-inch gap

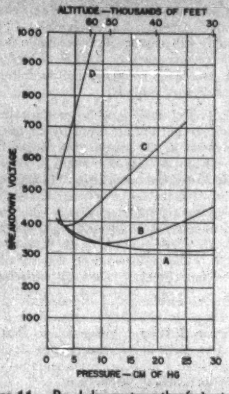

Figure 11. Breakdown strength of air at small spacings between rounded-edge, brass disks

Curve *A*—0.0004-inch gap
Curve *B*—0.002-inch gap
Curve *C*—0.008-inch gap
Curve *D*—0.040-inch gap

about $^1/_{32}$ inch thick. With this artifice, corona-like pulses appeared as low as 80 volts. A 4.5-volt Wheatstone bridge indicated a resistance of 74,000 ohms. Table III shows the type of variation found.

It is seen that these low values would probably cause trouble in the 208-volt system where they would not have affected the 28.5-volt d-c system. Because the effects of contamination were, as far as could be detected, nearly independent of pressure, it is probable that no corona difficulties will be introduced by the *change* from sea level to 50,000 feet.

The Dielectric Strength of Air as a Function of the Geometry of Electrodes

Figure 5 reveals an unexpected phenomenon. As shown by M. J. DeLerno,[1] the dielectric strength of air drops to one fourth of its sea-level value at about ten centimeters of mercury. However, the breakdown strength of the air gaps in

Table II. Corona-Starting Voltage of Number 8 Cable-to-Cable Sample Versus Moisture Content

Conditions	Corona-Starting Voltage
Dried by heat and drying agent	2,500
Room humidity	450
98-per cent humidity for eight hours	300
98 per cent humidity for 76 hours	1,400
Immersed in distilled water one minute	2,800
Immersed in distilled water 60 minutes	2,850

Table III. Effect of Water on Dust-Covered Surface

Pressure—cm of Hg	73.7	1.9	16.1	30.5	41.7	73.7
Corona-starting voltage	192	130	125	137	105	80

the capacitors remained almost independent of pressure over this range. An examination of the literature of the sparking potential of air yields the following very probable reason for this apparent inconsistency.

In 1892 J. B. Peace,[3] working with J. J. Thomson, obtained data for the curves that are replotted on Figure 11. On this graph it is shown that at very small spacings, such as at 0.0004 inch, the dielectric strength of air is not affected greatly by large changes of pressure. In fact the shapes of these curves are very similar to those of the corona curves of Figure 5.

Figure 12 shows the position of the air gaps where most corona occurs in capacitors. This position is known because corona markings are left on the paper. Below the corona-starting voltage the voltage across such a gap is a definite quantity, proportional to the total applied voltage and determined by the capacitor-divider effect of the dielectrics

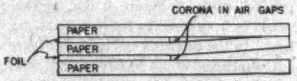

Figure 12. Section of capacitor showing position of corona at foil edge

in series. The gap is bound at each end by solid barriers and is subjected to an electric potential. The thickness of the metal foil is 0.0003 inch, and the breakdown path must be of comparable length. Therefore, the sparking potential of these gaps (and the corona-starting voltage of the capacitors) should, and do, show the same small dependence upon air pressure as did the 0.0004-inch and 0.002-inch gaps of Peace's data.

It becomes apparent that increasing the altitude has less effect upon the corona-starting and the breakdown voltages of small air gaps than large. The maximum effect of altitude is realized for large-plane parallel gaps where the pressure and the breakdown voltages are approximately proportional.[4] The minimum effect of altitude is realized in small air voids, such as in capacitors, where the breakdown and the pressure are nearly independent. An intermediate case is shown in Figure 9 on parallel studs where the variation of breakdown is less than proportional to pressure. A second intermediate case is shown by curve *D*, Figure 4, on dry cables. The air gaps between the cable insulations are relatively large in comparison with the capacitor air voids, and the corona-starting voltage is more dependent upon pressure.

An interesting fact found by Carr[4] is that with uniform fields the sparking potential of air, regardless of its gap spacing, temperature, pressure, or random ionization, will never fall below 351 volts (the fields of Figure 11 were not quite uniform). Covering more recent work by various observers, Loeb[2] makes the following statements: "A spark will not pass below about 275 volts in air no matter what the conditions. It is most important to realize that the minimum sparking potential exists and that below it a spark cannot pass. This fact is sometimes overlooked in practical application." By the word "conditions" he refers to the pressure, the temperature, the random ionization of the air, and the spacing and shape of the electrodes. If the temperature of the electrodes rises sufficiently to cause thermionic emission, such as in vacuum tubes or in restriking a-c arcs in circuit breakers, the air will permit the incidence of an electric current far below the 275 volts mentioned.

The voltages of this discussion are peak voltages. It is seen that neither corona nor breakdown will occur in air below about 195 volts rms.

An additional interesting point arises from the foregoing data. At high altitudes corona and breakdown in a capacitor which is safely rated for sea-level operations are more likely to occur around the bushings and internal leads to the

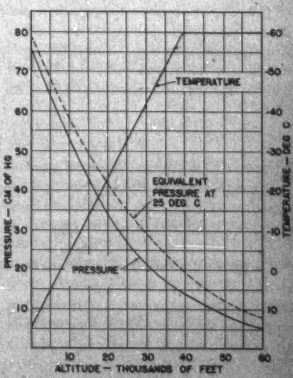

Figure 13. Change of atmospheric conditions with altitude

bushings than in the capacitor rolls. If the capacitor is completely filled with a liquid dielectric, or if it is gas filled and well sealed, the reduction of pressure with altitude will reduce the electric strength of only the external portions of the bushings. However, if the internal leads are in air and the pressure of that air drops with altitude, an unsafe condition may exist. Imagine a capacitor consisting of, for example, ten series sections of the roll of Figure 5, curve *A*. Even if the capacitor were not hermetically sealed, the corona-starting voltage of the rolls in series would remain fairly constant at about 3,000 volts, which is ten times the corona-starting voltage of the single roll. However, the breakdown voltage of the bushings and of the internal leads (if in air) would drop to below 351 volts if the pressure were reduced sufficiently.

Corrections for Low Temperatures at High Altitudes

High-altitude conditions were approximated by use of the data of Figure 13. The dotted portion of the temperature curve represents a rough average of the variable temperatures which occur in that region. No attempt was made to reproduce the low temperatures of high altitudes because Paschen's law, as stated by Cobine,[4] makes it possible to perform tests in air at room temperature which are equivalent to tests at other temperatures. Paschen's law states mathematically that for any given electrode configuration, changes in the temperature and pressure of the air will not change the sparking potential (the writer adds corona-starting voltage) unless they change the density of the air. The density of the air is proportional to the ratio of pressure to absolute temperature, and if this ratio stays constant the density will stay constant also. Thus, two tests will be equivalent and will yield the same corona-starting or breakdown voltage in air if

$$Pa/Ta = Pe/Te \qquad (1)$$

where Pa, Ta are the absolute pressure and temperature of the application conditions, and Pe, Te are the absolute pressure and temperature of the equivalent test.

All tests were run at about 25 degrees centigrade, or 298 degrees Kelvin ($Te = 298$). Therefore the corona or breakdown values for any electrode configuration in air at any altitude (or at any moderate temperature and pressure) may be found from room temperature data by substituting the pressure Pa and temperature Ta for that altitude in the following expression:

$$Pe = 298(Pa/Ta) \qquad (2)$$

The corrected voltage can be taken from the room temperature curve at pressure (Pe). In this manner the curve of equivalent pressure at 25 degrees centigrade, plotted on Figure 13, was obtained. The equivalent altitudes shown on the graphs were, in turn, taken from this curve.

For example, at 35,000 feet the temperature averages minus 54.3 degrees centigrade, or 218.7 degrees Kelvin ($Ta = 218.7$). The pressure averages 18 centimeters of mercury ($Pa = 18$). The substitution of these values in equation 2 yields an equivalent pressure of 24.6 centimeters of mercury. The effect that this low-temperature correction has on corona-starting or breakdown voltages depends upon the shape and spacing of the electrodes. For large-plane parallel gaps, the change in voltage would be proportional to the change in pressure. The breakdown voltage would be increased by the ratio of 24.6 to 18, or by 36 per cent. On the three-eighth-inch parallel studs of Figure 9 the increase would be from 3,700 to 4,400, or by 20 per cent. In the capacitor of curve *A*, Figure 5, the increase would be from 285 to 292, or only 2.4 per cent. It is interesting to note that on curve *B* of Figure 5 and on curves *A* and *B* of Figure 11 the lowering of temperature at 60,000 feet *decreases* the corona-starting and breakdown voltages. Thus, it cannot be said that data taken at high-altitude pressures and at room temperature are always conservative, though this is usually the case.

Conclusions

1. Two tests revealed corona-like disturbances at voltages low enough to approach 208 volts. The tests were on moist contaminated surfaces and on moist aircraft cables. Therefore, conditions of high moisture in the 208-volt 400-cycle electric system should be avoided or investigated by means of life tests.

2. The low corona-starting voltages were nearly independent of pressure. Therefore, the change from steady-state operation at sea level to steady-state operation at 50,000 feet will produce no difficulties with corona in the proposed system.

3. The change in frequency from 60 to 400 cycles per second will produce no appreciable change in the corona-starting voltages of cables, air gaps, and capacitors. It very probably will produce no appreciable change in the corona-starting voltage of any electrode and field configuration in industry. (Figure 1 and Table I.)

4. M. J. DeLerno[1] has shown that the dielectric strength of air drops by as much as 75 per cent as the pressure is reduced from 76 to 8.7 centimeters of mercury (0 to 50,000 feet at 25 degrees centigrade). In this paper for the same change in pressure the greatest drop in corona-starting voltage (the breakdown of small air voids and gaps) was by a factor of 71 per cent (Figure 4, curve *D*, cables). The smallest drop was by about 20 per cent (Figure 5, curve *A*, capacitors).

5. In the insulation of the aircraft cables the change in moisture content from a dry condition (Figure 4, curve *D*) to that assumed at room humidities (Figure 3, curve *A*) produced a drop in corona-starting voltage by as much as 84 per cent.

6. In low-voltage capacitors which are not hermetically sealed and contain air voids, it appears that the corona-starting voltage will not be reduced more than about 30 per cent even if the capacitors be elevated above 60,000 feet (Figure 5). No trouble should be expected from corona in the capacitor rolls at high altitudes, but the corona-starting and breakdown voltages of the bushings will be greatly decreased.

7. Tests were made with parallel studs extending perpendicularly from a clean insulating surface at spacings of one-fourth and three-eighths inch between threads. No corona existed before breakdown at pressures from 1 to 76 centimeters of mercury (Figure 9).

8. Between needle gaps the air would sustain steady-state corona without breakdown at high pressures. At low pressures, breakdown would occur without any sign of preceding corona (Figure 10).

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Polarized-Light Servo System

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Synopsis: A new servo system has been developed in which the connecting link between the primary and secondary shafts is polarized light whose plane of polarization rotates with the primary shaft. This makes possible the accurate following of the rotation of the primary shaft without any load being imposed on it. This servo system has been applied successfully in several electro-mechanical calculating machines.

SERVO mechanisms or follow-up systems are used in many recording and control devices to amplify small forces or torques so that the motion of a heavily loaded output mechanism will correspond closely to the motion of a very low torque input element.[1–3]

Polarized-Light Follow-up System

In an electromechanical calculating machine, it was desired to control the motion of an output mechanism to correspond closely to the rotation of a small integrating wheel which rolled on the surface of a revolving turntable.

The requirements, not fully met by existing follow-up systems, were:

1. The follow-up system must impose no load or restraint on either the integrating wheel or its bearings.
2. It must permit free axial movement of the wheel.
3. It must operate to follow continuously the rotation of the wheel in either direction.
4. It must be able to follow rapid accelerations and decelerations of the wheel.

To fulfill these requirements, a servo system was developed which makes use of polarized light[4] as the connecting link between the input and output mechanisms.

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Principle of Operation

The principle of operation of the polarized-light servo system is shown diagrammatically in Figure 1. In this system a small integrating wheel rolls on the surface of a turntable, at an adjustable radius r.

Attached to the same shaft (primary shaft) and rotating with this shaft and integrating wheel is a light polarizing disk or primary polarizer. Two beams of light (A and B) passing through the primary polarizer are polarized similarly, and the plane of polarization rotates as the primary shaft rotates.

A secondary shaft is, in effect, coupled to the primary shaft by means of these two rotating beams of polarized light in the following manner. The two beams of light fall on two phototubes after each has passed through a separate secondary or control polarizer. These two secondary polarizers are attached to the secondary shaft in such a manner that their planes of polarization are at right angles to each other.

When the primary polarizer is oriented so that its plane of polarization is half way between, or at an angle of 45 degrees with both of the secondary polarizers, equal amounts of light will strike both phototubes. If the plane of polarization is not at 45 degrees to both secondary polarizers, unequal amounts of light will strike the phototubes. Thus, if the primary polarizer is rotated from balance a small amount in one direction, the light on one phototube is reduced because the angle between the two polarizers in that beam becomes more nearly zero, with a corresponding increase in light on the second phototube. If the primary polarizer is rotated in the other direction, the light beams are unbalanced in the other direction.

The unbalanced output of the phototubes is amplified and controls the speed and direction of rotation of the servomotor, and thereby the secondary shaft and polarizers, to keep the light on the phototubes always at or near balance.

There are four positions of the primary shaft with respect to the secondary shaft where the light beams may be balanced. Only two of these positions, however will give a condition of stable balance. Once the condition of stable balance has been established it is maintained, and the secondary shaft will rotate with the primary shaft in either direction within the allowable limits of speed, acceleration, and load as determined by the motor and amplifier characteristics.

The axis of the primary shaft is held by bearings parallel to the plane of the turntable surface. For changes in radius of contact of the integrating wheel, the primary shaft and polarizer can be moved axially along the two light beams without materially affecting their balance.

Figure 1. Schematic diagram of polarized-light servo system

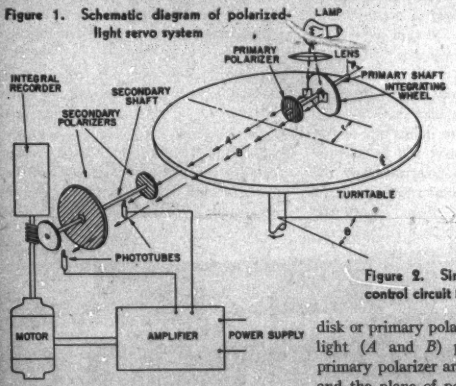
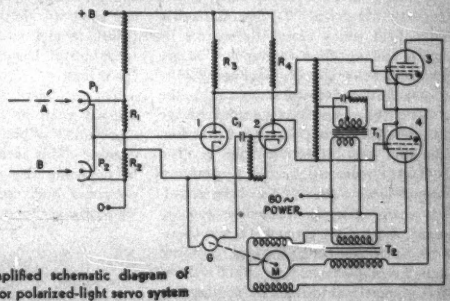


Figure 2. Simplified schematic diagram of control circuit for polarized-light servo system



Electronic Circuit

Figure 2 is a simplified schematic diagram of the control circuit. The two light beams fall on phototubes P_1 and

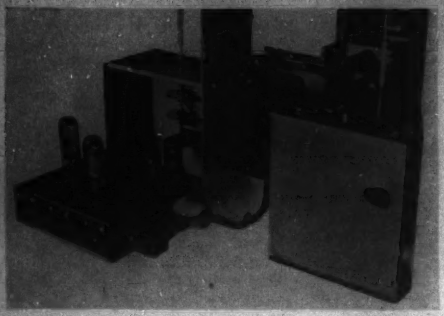


Figure 3. Polarized-light servo system for integrating pressure traverse recorder

P_2 which form two legs of a bridge circuit comprised of R_1, R_4, and the resistances of the two phototubes. The voltage unbalance of this bridge is applied between grid and cathode of vacuum tube 1. This tube together with tube 2 and resistances R_3 and R_4 form a second bridge circuit whose output is applied to the grids of two thyratron tubes 3 and 4.

The anode currents of the thyratrons, supplied from the 60-cycle power source through transformer T_2, flow through a split field series motor to control its speed and direction in response to unbalance of the light beams A and B.

A small d-c generator is attached to the shaft of the motor, and its output voltage is applied through a capacitor C_1 between the grid and cathode of tube 2. The voltage e generated by this generator is proportional to the speed ω of the secondary shaft. For the frequencies encountered, the current through C_1, and therefore the voltage across the grid resistor of tube 2, is proportional to de/dt and is therefore proportional to $d\omega/dt$ the acceleration of the output shaft. Thus, the condition of balance of the two light beams is anticipated, and the system is stabilized and remarkably free from the hunting or oscillation commonly experienced in servo systems.

It will be noted that a single lamp is used as a light source for both beams of light so that any changes in the light output due to aging, darkening of the bulb, and input voltage affect equally the light falling on both phototubes, causing no unbalance of the system. The bridge circuits employed also make the electronic circuits relatively free of unbalance because of supply voltage fluctuations.

The torque-angle characteristics of the polarized-light servo system are dependent on the characteristics of the amplifier and motor. Within operating limits the torque is approximately proportional to the relative angular displacement of the light polarizers at any given speed. Series-motor characteristics make possible very high torques for rapid acceleration and deceleration. No accurate measurements of maximum accelerations and decelerations have been made, but it is estimated that the primary shaft can accelerate or decelerate at 2,000 rpm per second or more before the secondary shaft will drop out of synchronism. Speeds as high as 1,500 rpm have been used, but this is not necessarily the upper speed limit.

The secondary shaft will follow the primary shaft in angular position with an accuracy of plus or minus one or two degrees. This accuracy will be affected by nonuniformity of polarization in the polarizers and nonuniformity of light transmission through them. Since the primary and secondary polarizers normally operate at 45 degrees to each other, the rate of change of light transmission with respect to angular displacement is a maximum. Therefore, the angular errors due to variations in the polarizers are at a minimum.

Applications

Integration

The polarized-light servo system is being used successfully in new electromechanical instruments for solving accurately problems involving integration. Refer to Figure 1; the radius r at which the integrating wheel rolls on the turntable is variable by means of a cam or screw and represents the integrand.

If θ is the angular displacement of the turntable, the angular displacement of the integrating wheel and primary shaft ρ is proportional to $\int r d\theta$.

$$\rho = k \int r d\theta$$

The angular displacement of the secondary shaft is the same as that of the primary shaft and integrating wheel, and since considerable power is available to drive this shaft, it can be loaded to drive other calculating and recording mechanisms. The primary shaft is held in alignment by jewel bearings and is balanced so that radial and thrust loads are substantially zero. Since there can be no restraining torque on the primary shaft because of loading of the secondary shaft, the integrating wheel rolls on the turntable with negligible slippage and correspondingly high accuracy.

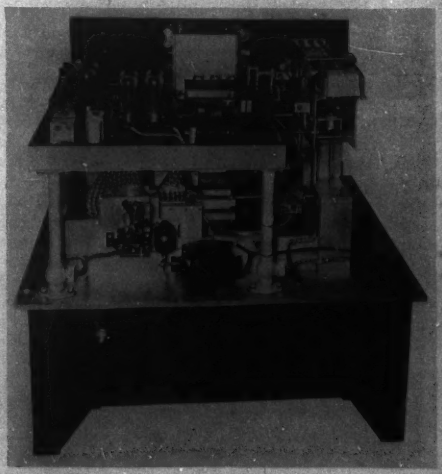


Figure 4. Integrator unit (without cover) for automatic integrating pressure traverse recorder. Rear view

Figure 3 shows a polarized-light servo system as used in the new General Electric integrating pressure traverse recorder, a specialized calculating machine which employs two follow-up systems as integrators. The phototube amplifier is tipped down to show its construction and the secondary polarizers.

The secondary shaft is at right angles to the primary shaft, and the light beams are changed in direction by means of mirrors. The phototube amplifier for the second integrator is shown at the lower right in operating position.

Figure 4 displays the same machine which shows the cams for moving the integrating wheels on the turntables. The driving motors and thyratron controls are on the shelf above the turntables and cams.

Figure 5 is a front view of the calculating and recording unit of the integrating pressure traverse recorder which is used by the research section of the General Electric turbine engineering division in its air test laboratory for studying flow phenomena through turbine passages. In this machine the integrated values will check each other within 0.01 per cent on repeated integration of the same function. These errors can be due largely to mechanical tolerances. This indicates that the slippage of the integrating wheel on the turntable is extremely small.

A special integral recorder on this device makes possible the reading of integrated values to the precision required for such measurements.

Figure 6 shows the General Electric differential analyzer[5] which is used in solving problems involving the use of differential equations. This machine has fourteen integrating units, each with its polarized-light servo system.

Figure 5. Integrator unit for automatic integrating pressure traverse recorder

Speed Measurement

In another application a variation of this servo system has been used to measure accurately over a wide range the speed of a large rotating machine. The turntable is driven at a constant and accurately known speed by a synchronous motor from a regulated frequency source. The secondary polarizers are driven by the machinery whose speed is to be measured and the wheel is positioned on the turntable so that it follows the secondary polarizers; thus the radius of the wheel on the turntable is an accurate measure of the unknown speed. Speed measurements have been made to 0.025 per cent accuracy for primary shaft speeds up to 1,300 rpm.

Differentiation

In the measurement of speed as already described, the servo system is actually used as a differentiator in which the angular displacement of the secondary polarizers ρ' may be expressed by the equation:

$$\rho' = \int \omega_1 dt$$

where ω_1 is the angular velocity of the control polarizers.

The angular displacement of the primary polarizer ρ is expressed by

$$\rho = k \int r d\theta$$

$$d\theta = \omega_2 t$$

where ω_2 is the angular velocity of the turntable.

$$d\theta = \omega_2 dt$$

If $\rho = \rho'$, then

$$d\rho = d\rho' = \omega_1 dt = k\omega_2 \cdot dt$$

and

$$\omega_1 = \frac{d\rho'}{dt} = \frac{d\rho}{dt} = k\omega_2 r$$

Since ω_2 is constant,

$$\frac{d\rho'}{dt} = Kr$$

When used as a differentiator, the servo system is inherently oscillatory, but by taking the proper steps the oscillations can be highly damped.

Conclusions

The new servo system using plane polarized light as the interconnecting link between the primary and secondary mechanisms makes possible the driving of heavy loads with accurate following of primary shaft without imposing any restraint or reaction upon its motion, either in the direction of rotation or axially.

Figure 6. Differential analyzer showing 14 integrator-unit assemblies

Electric-Circuit Burning-Clear and Damage Phenomena on Aircraft Structures

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Synopsis: Normal and continuous performance of electric circuits is a prerequisite to the effective use of airplanes. Electric short circuits which result in the loss of power for vital control operations or which cause fires are definite hazards. The extensive use of the 28.5-volt d-c aircraft systems, the proposed 120-volt d-c system, and the consideration being given a three-phase 120–208-volt a-c grounded neutral system for high-altitude planes necessitated an investigation into the burning-clear and damage phenomena on all circuits. Short circuits were applied on an aluminum-alloy section of an airplane, and oscillograms of short-circuit current and voltage taken. In both the a-c and d-c systems it was found that the fault-damage and burning-clear phenomena depended upon the energy level in the short-circuit area. When the contact area between the conductor and aircraft structure was small, the energy level was high, and the fault burned itself clear. In such cases the aircraft structure was perforated. Increase in contact area and a consequent reduction in energy concentration resulted in a sustained fault current. In some of these cases a definite welding of the conductor to the aircraft structure occurred, while in others no burning took place.

The General Problem

IT is generally accepted that the correct performance of the electric system is vital to the effective use of an airplane. Electric-wiring faults, such as short circuits resulting from gunfire or other causes, may result in faulty control or fire hazard. Experience has shown that on the commonly used 28.5-volt d-c systems such short circuits are often self-clearing, and serious consequences do not result. However, this is not always the case, and it is possible that a significant number of airplanes have not returned from the combat area because of damage to the electrical system. Accordingly, it was felt advisable to investigate the conditions under which faults may be expected to clear and to determine the magnitude of current and length of time required to cause serious damage to the aircraft structure when a short circuit occurs. It should be recognized that, in practice, where circuit protection is used the fault duration and damage may be limited by this protective equipment which would remove the faulty circuit from the system. Such protection was not used in the tests as they were intended to show the effects of short circuit where system protection was not involved. Circuit protection is discussed in a companion paper.[1]

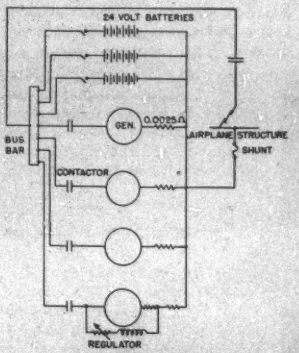

Figure 1. Aircraft electrical system as adapted for burning-clear tests

Since consideration is also being given to a three-phase 120–208-volt 400-cycle a-c grounded neutral system (120 volts to ground), and to a 120-volt d-c system, similar investigations using such power systems were carried out.

The Investigational Method

The basis of the investigation was a series of direct full power short-circuit tests made in the laboratory with a portion of aircraft structure as test piece. A diagram of connections of the circuit for the 28.5-volt d-c system is given in Figure 1. This circuit is an adaptation of a typical electric circuit for a four-engined airplane such as the "Flying Fortress" and is, as nearly as is possible, a duplicate of the actual system. Each of the four *Pl* aircraft generators (200 amperes 28.5 volts) was driven by a ten-horsepower 3,600-rpm induction motor supplied from a variable frequency source. The negative terminal of each generator was connected through a resistance of 0.0025 ohm to a common point, while the positive terminals were tied to a single bus. Three batteries could be paralleled with the generators by means of single-pole switches. Time, current, and voltage values for each short circuit were determined by means of an automatic magnetic oscillograph.[2]

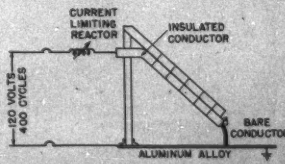

Figure 2. Arrangement of test sample for single-phase-to-ground 400-cycle burning-clear tests

As a test specimen representative of an aircraft structure, part of a wing section and nacelle of a "Flying Fortress" was used. To this was attached the negative terminal of the supply system. The positive terminal of the system was connected through a contactor to a length of 1/0 aircraft cable, one end of which rested perpendicularly on the aircraft structure; short circuits were applied by closing the contactor. The position of the conductor

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Several applications have been made in integrating and differentiating unit of special electromechanical calculating and measuring devices for solving complicated problems accurately and quickly.

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was chosen because cables running parallel to the aircraft fuselage and subsequently severed by gunfire can be bent so as to contact the structure perpendicularly. The effects of a short circuit brought about in this way are the most severe.

With the generators operating at 3,000 rpm and an open-circuit voltage of 28.5 volts, and at first with no batteries in the circuit, short circuits as previously mentioned were applied to various sections of the aircraft structure by closing in the line contactor. The supply system was then augmented by one battery, then two, and finally three batteries in parallel with the generators and the tests repeated.

structure and cable were covered with a bell jar which was evacuated to a pressure corresponding to the required altitude.

Data on the 120–208-volt a-c system were obtained in the course of separate tests in which power was obtained from three single-phase transformers supplied by means of a motor generator set. A diagram of connections for single-phase-to-ground faults is given in Figure 2. Variations in current level were obtained by means of taps on air-cored reactors connected in series with the transformer and by connecting two or three transformers in parallel. The current range investigated was selected to cover the possible number and sizes of generators operating in parallel on certain aircraft systems.

Using 0.020-inch and 0.25-inch aluminum alloy, short circuits as in the foregoing were applied at different current levels and with various sizes of conductor. Similar tests were carried out in a steel chamber evacuated to a pressure corresponding to an altitude of 40,000 feet. Further short circuits were applied to 0.10-inch magnesium alloy, at sea level and at a pressure corresponding to an altitude of 40,000 feet, and to generator end shields of magnesium alloy.

Analysis of Results

Both the d-c and a-c tests brought out very decisively that there are two widely different results of short circuit; these are referred to in the following as "self-clearing" and "weld." By the former is meant melting and vaporizing of the metal in the vicinity of the short-circuit area and its explosive expulsion from the arc, resulting in a complete clearance of the short circuit. A weld takes place when only sufficient energy is involved in the short circuit to result in a permanent connection between the conductor and airplane structure.

Oscillograms representative of self-clearing and weld faults are given in Figures 3 and 4, respectively, for the d-c system, and in Figures 5 and 6, respectively, for the a-c system. Figure 7 shows the progress of a typical short circuit while Figure 8 is illustrative of the damage to the aircraft structure as a re-

Table I

Test	System	Number of Generators	Number of Batteries	Current (Amperes)	System Condition Prior to Short Circuit	Type of Material	Cable Size (Number)	Insulation	Altitude	Results
Short circuit	28.5-volt direct current	Four	None	Up to 4,500	No load	0.020-inch to 1/8-inch Al (alloy)	1/0	Deltabeston	Sea level	Self-clearing and sustained
Short circuit	28.5-volt direct current	Four	One	Up to 4,500	No load	0.020-inch to 1/8-Al (alloy)	1/0	Deltabeston	Sea level	Self-clearing and sustained
Short circuit	28.5-volt direct current	Four	Two	Up to 4,500	No load	0.020-inch to 1/8-inch Al (alloy)	1/0	Deltabeston	Sea level	Self-clearing and sustained
Short circuit	28.5-volt direct current	Four	Three	Up to 4,500	No load	0.020-inch to 1/8-inch Al (alloy)	1/0	Deltabeston	Sea level and 40,000 feet	Self-clearing and sustained
Short circuit	28.5-volt direct current	Four	Three	Up to 4,500	Loaded	0.020-inch to 1/8-inch Al (alloy)	1/0	Deltabeston	Sea level and 40,000 feet	Self-clearing and sustained
Short circuit	28.5-volt direct current	Four	Three	Up to 4,500	No load. Resistance added to external circuit	0.020-inch to 1/8-inch Al (alloy)	1/0	Deltabeston	Sea level and 40,000 feet	Self-clearing and sustained
Short circuit	28.5-volt direct current	Four	Three	Up to 4,500	No load	0.020-inch to 1/8-inch Al (alloy)	1/0	Deltabeston, glass-cotton, 100 per cent glass	Sea level and 40,000 feet	Self-clearing and sustained
Short circuit	120-volt direct current	—	—	Up to 2,000	No load	0.020-inch to 1/8-inch Al (alloy)	1/0	Deltabeston	Sea level and 40,000 feet	Self-clearing and sustained
Short circuit	120-volt 400 cycles alternating current	—	—	Up to 2,500	No load	0.016-inch to 1/4-inch Al (alloy)	16 to 1/0	Deltabeston	Sea level and 40,000 feet	Self-clearing and sustained
Short circuit	120-volt 400 cycles alternating current	—	—	Up to 2,500	No load	0.010-inch Mg	1/0	Deltabeston	Sea level and 40,000 feet	Self-clearing and sustained
Short circuit	120-volt 400 cycles alternating current	—	—	Up to 2,500	No load	Mg end shields	1/0	Deltabeston	Sea level and 40,000 feet	Self-clearing and sustained
Short circuit	208-volt 400 cycles alternating current	—	—	3,700	No load	Copper to copper	16 to 1/0	Deltabeston	Sea level and 40,000 feet	Self-clearing and sustained
Gunfire	24-volt direct current	—	1,500 amperes capacity	Up to 1,500	No load	0.016-inch to 1/8-inch Al (alloy)	16 to 1/0	Deltabeston, glass-cotton, 100 per cent glass	Sea level	Self-clearing and sustained

A considerable number of tests was carried out with three batteries in the system, and the effects on the short circuit of load on the system, of increased short-circuit resistance, and of simulated high altitude were investigated. For the altitude tests a small section of 0.020-inch aluminum alloy and a piece of 1/0 cable touching the alloy perpendicularly were set up on a platform to which supply terminals had been connected. The

sult of short circuit. Table I summarizes the test program and test results.

28.5-Volt D-C System

(*a*) *Effect of Batteries.* Although the electric supply system of the "Flying Fortress" airplane consists of four generators and three batteries in parallel it was felt advisable to study the effect of varying the number of batteries. The results here compared with the general trend of results throughout all the tests. Whenever the contact pressure between the cable and aircraft structure was such that only a few strands of the cable touched the aluminum alloy, whether the latter were skin, bulb angle, or rib, the

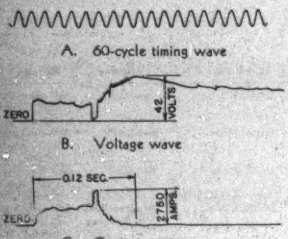

Figure 3. Oscillogram showing self-clearing d-c fault

Time of short circuit 0.12 second. Maximum current 2,750 amperes. Maximum voltage 42 volts

fault was self-clearing and often accompanied by heavy arcing and explosive scattering of molten aluminum-alloy particles. In most cases the fault did not burn clear until the structure was perforated. However, there were instances when the cable melted at a sufficiently high rate to open the circuit before the perforation was complete.

With the pressure between the cable and airplane structure such that the contact arc was large, the short circuit was continuous and did not burn clear. In some cases a weld was produced while in others there was no visual damage either to cable or aircraft structure. As the number of batteries increased, a greater pressure was required to produce a short circuit which would not burn clear.

When the contact is light, only a few strands of cable form the short circuit with the airplane structure. Thus at the instant of establishment of the short circuit, the concentration of energy is extremely high, causing the copper and aluminum alloy to melt superficially and an arc to strike. This arc continues until the fault clears either because of a structural perforation, or because of rapid melting of the cable.

If the contact pressure between cable and structure is high, the contact area is much larger and, therefore, the energy concentration greatly reduced. In general this energy concentration is insufficient to cause initial melting of the cable or aluminum alloy, and no arc results; the fault is continuous and sustained. The ampere capacity of the system increases with an increase in the number of batteries and, therefore, for the short-circuit energy concentration to be maintained at a level low enough to cause continuation of the short circuit, a greater pressure is required for each battery addition. Thus a system having a small ampere

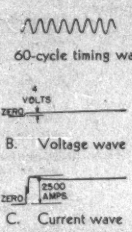

Figure 4. Oscillogram showing d-c short circuit resulting in weld

Maximum current 2,500 amperes

capacity will probably produce more welds due to short circuit than one with a large ampere capacity, since less pressure is required in the former case.

The oscillogram of Figure 3 is illustrative of a self-clearing fault. The effect of the field regulator can be seen during arcing periods, the generator voltage rising with current flow. Rapid and irregular variations in the voltage wave, caused by abrupt changes in resistivity within the arc and movement of the cathode spot, are plainly visible. When the current reaches its final zero and the fault clears, the rise of recovery voltage and its slow decay to normal open-circuit value are clearly recorded.

An oscillogram characteristic of a short circuit resulting in a weld is given in Figure 4. After the initial peak the current assumes its steady-state value, and no arcing takes place.

(*b*). *Effect of Load on System (Four Generators, Three Batteries).* When the system is loaded prior to the application of the short circuit, the values of short-circuit current, the resulting damage both to cable and structure and the time of short circuit are in general the same as for four generators and three batteries in parallel without load. The peak value of the short-circuit current is reached more quickly after short circuit, however, by virtue of the fact that with load on the system the main field strength is high and the armature current is already about one fifth of the value of short-circuit current.

(*c*). *Effect of Increased Short-Circuit Resistance.* The effect of increasing the short-circuit resistance was similar to lowering the ampere capacity of the electric system. Thus with higher values of resistance the possibility of a weld is increased. Faults remote from the airplane bus are therefore more likely to result in a weld because of current limitations due to increased circuit resistance.

(*d*). *Effect of Altitude.* At pressures corresponding to higher altitudes, arcing persisted somewhat longer, al-

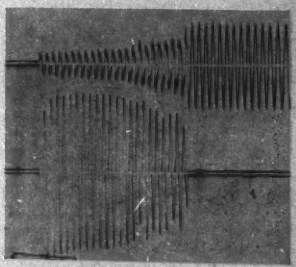

Figure 5. Oscillogram showing self-clearing a-c fault

Time of short circuit 0.052 second. Maximum current 2,000 amperes. Maximum voltage 120 volts

Upper curve—Voltage
Lower curve—Current

though current and voltage values were about the same as those obtained at sea level. Increasing contact pressure between the cable and airplane structure resulted again finally in a weld. When the short circuit resulted in perforation of the aluminum alloy the hole was more clear-cut than at sea level due to decreased oxidation. The molten alloy was scattered with explosive violence in a direction perpendicular to the structure and away from the conductor, but there was little evidence of molten copper. No appreciable change in pressure inside the bell jar was noticed during each short circuit.

120-Volt D-C System

Exploratory tests at sea level and a pressure corresponding to an altitude of 40,000 feet with a 120-volt d-c system were carried out. The results followed the same trend as those obtained with the 28.5-volt d-c system and the 120–208-volt a-c system, faults either burning clear or resulting in a weld, the governing factors being as stated previously. In some cases arcs approximately half an inch long were obtained.

120–208-Volt A-C System

(a). *Phase-to-Ground Fault on Aluminum Alloy, at Sea Level.* With a supply system of 120–208 volts alternating current, the effects of short circuit again fell into the two categories—self-clearing and weld. When the contact between the conductor and airplane structure was light, and therefore the contact area small, whatever the size of conductor, type of structure, or current level involved, the fault was self-clearing, and an arc formed. In all cases the arcing was severe, though rarely prolonged, and was accompanied by explosive scattering of molten metal. Small fires were started within a radius of ten feet from the short-circuit area, the test floor being covered with a thin layer of sawdust and some oil.

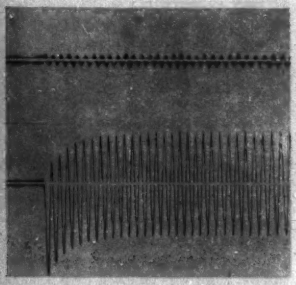

Figure 6. Oscillogram showing a-c short circuit resulting in weld

Maximum current 670 amperes

Upper curve—Voltage
Lower curve—Current

Faults which were not self-clearing fell into the second category of a "weld or sustained short circuit." In these instances the material, or the shape of the part of the aircraft structure concerned, was not important, the principal factors being the current level and cable size. Thus, for a given current level, the smaller the conductor the greater is the contact pressure required to produce a weld. For a given conductor size, in order to produce a weld, the contact pressure required is much less the lower the current level. Short circuits occurring in remote sections of an aircraft electric circuit may readily result in welds or be sustained, unless the fault was otherwise interrupted. Figure 8 illustrates damage from short circuit to a section of an airplane. The damaged area identified by the number 8 is representative of a short circuit resulting in a weld while the remaining areas are perforations from self-clearing faults.

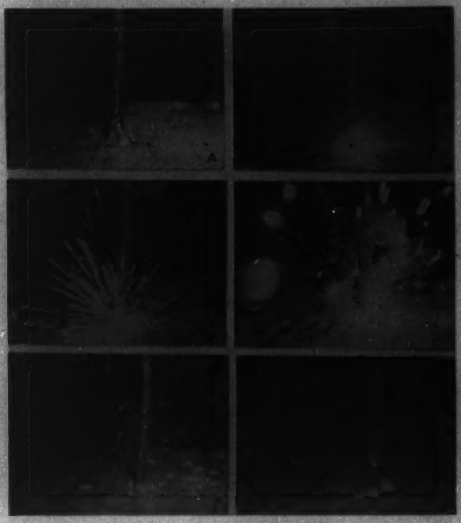

Figure 7. Progress of short circuit resulting in perforation of aircraft structure

Gunfire Tests

Parallel conductors were mounted inside and one inch from an aircraft section and connected at one end to a bus fed from a 24-volt battery. The other ends of the conductors were insulated and the aircraft section connected to the negative terminal of the battery. With a range of approximately 100 yards, 50-caliber-machine-gun bullets were fired at the test piece so that they would strike the conductor on the leaving side. In almost every case faults were produced and in one instance, as shown at *A* in Figure 9, the conductor welded to the structure. Damage both to conductor and structure, due to short circuit, was insignificant in comparison with the damage caused by gunfire.

Further bullets were fired so that they would strike a conductor on the entering side. In such cases a self-clearing short circuit occurred when the conductor contacted the structure as the former swung back into position after being severed by the bullet impact.

Whenever a conductor was severed by gunfire, about one inch of insulation was torn off on both sides of the break, and the conductor strands were spread brush fashion. Although in general only a few strands subsequently formed the short circuit, in one instance most of the cable cross section contacted the aircraft structure. In this case a weld was produced, as stated previously.

Three small areas of the aircraft section were covered with a thin coat of insulating varnish. In these areas faults occurred only when a severed conductor contacted the edge of a perforation produced by gunfire.

Genera Interpretation

The physical aspects of the d-c and a-c short circuits were similar, and pictures shown in Figure 7 serve to illustrate the progress of a self-clearing short circuit on either system. Evidence of explosive scattering of molten metal in Figures 7e and 7f, just before the fault clears, indicates that the formation of the perfora-

Figure 8. Electric-fault damage to aircraft structure

3, 4, and 5—Self-clearing fault. 1,120 amperes, number 16 cable

6—Self-clearing fault. 2,000 amperes, number 8 cable

7 and 9—Self-clearing fault. 665 amperes, number 8 cable

8—Welded fault. 665 amperes, number 8 cable

11 and 12—Self-clearing fault. 1,970 amperes, number 8 cable

tion required a time about equal to the duration of the short-circuit current. As the short circuit progresses, the conductor melts, and a pool of molten aluminum alloy is formed; meanwhile gases in the arc throw out particles of alloy explosively. The oscillogram presented in Figure 5 indicates intermittent arcing. Examination of the conductor after a fault cleared usually showed that during the short-circuit period drops of molten copper had formed. Apparently these droplets under arc forces are elongated toward the airplane structure and finally break free from the conductor. The formation and breaking off of the droplets correspond to the striking and extinguishing of the arc. The process is repetitive until the aluminum alloy is very thin and can no longer withstand the gas pressure in the neighborhood of the arc; the perforation is then formed explosively, and the fault clears permanently.

The increase in measured voltage indicated in the oscillogram of Figure 5 is due to a slight increase in arc length.

(*a*) *Phase-to-Ground Fault on Aluminum Alloy, at High Altitude.* Both the self-clearing and weld type of short circuit were substantially independent of barometric pressure corresponding to high altitude. The duration of the former type was generally the same as at sea-level pressure, and the extent of damage was unchanged except for decreased oxidation at high-altitude pressures. Because of this the perforations were more clean-cut than at sea-level pressure.

(*b*) *208-Volt Phase-to-Phase and Three-Phase Faults.* Phase-to-phase faults on various sizes of wires and three-phase faults fell into categories of self-clearing and weld, the current level and contact pressure affecting both as before. In those instances when the fault cleared, the conductor melted back into the insulation until the voltage could no longer maintain the arc. The insulation was not damaged severely. When the fault was not self-clearing, the cable became overheated and would be severely damaged unless the fault were cleared by other means. Results at high-altitude pressure were similar.

(*c*) *Phase-to-Ground Fault on Magnesium Alloy, at Sea Level and High Altitude.* Two forms of magnesium alloy were used, the first being 0.10 inch thick with a painted surface finish and the second an aircraft generator end shield.

The insulating properties of the painted surface finish on the former were sufficient to prevent an arc from striking when voltage was applied. However, when the surface finish was removed over a small area and the conductor applied there, a short circuit occurred with results similar to those for aluminum alloy both at sea-level pressure and in a rarefied atmosphere. The magnesium-alloy plate did not ignite, but burning particles were scattered explosively and continued to burn for some time.

Similar results were observed with the magnesium-alloy end shields.

In all tests on the magnesium alloys the current level was maintained at approximately 2,000 amperes.

Résumé of Results

The general phenomena of burning clear and welding as presented in the foregoing admit of further statements as follows on particular aspects of the short-circuit problem.

1. When the energy concentration at the fault is high (high current, low contact area) the short circuit is generally self-clearing. Thus, the higher the current level the greater is the likelihood that faults will burn clear. There would be less danger of a weld due to the higher contact pressure required.

2. Fault damage to the aircraft structure was similar for the 28.5-volt and 120-volt d-c systems as for the 120–208-volt a-c system. However, on the a-c and 120-volt

d-c systems, in almost every case, fault current flowed when the conductor and aircraft structure came into contact. With the 28.5-volt d-c system, oxide films sometimes prevented this.

3. Because high energy concentration at a fault results in self-clearing of the latter, at a given current level, the smaller the wire the greater is the likelihood of a fault being self-clearing, and the resulting structural damage is less. All wires capable of carrying a current without conductor disintegration can produce a sustained short circuit and perhaps a weld.

4. Insulations with a low melting point tend, on short circuit, to withdraw from the short-circuit area, thus exposing more conductor and increasing the danger of prolonged short circuit. The outer cotton braid usually burns to cause a distinct fire hazard. With higher melting point insulations, the binding material may disintegrate without damage to the insulation, but the latter generally has low resistance to abrasion. The thickness of the insulation used is sufficient to prevent initiation of a short circuit.

5. In the range of material thicknesses covered by the tests no appreciable difference in reaction to short circuit was noticed. However, as the thickness of the structural material increases, when a short circuit is applied, a pool of molten material is more readily formed, and thus the danger of a weld is increased.

6. At pressures corresponding to higher altitudes structural perforations are more clean-cut because of decreased oxidation. On the 28.5-volt d-c system this latter effect will increase the possibility of short circuit from an accidental contact (see paragraph 2).

7. With a light-pressure type of contact (small contact area), a fault is self-clearing for any placement of the conductor. Thus the initial type of contact between the aircraft structure and the conductor, except as regards pressure, is relatively unimportant.

8. Vibration of the airplane structure increases the fault duration and the resulting damage. An accidental contact is likely to produce a fault at any voltage because of abrasion of the contact surfaces (see paragraph 2), and the arc may be re-established after clearing.

9. Of the materials tested, fire danger due to the scattering of molten metal particles was greater with magnesium because of the tendency of the particles to continue burning. No other significant difference was noted between the aluminum and magnesium alloys using copper-wire conductors.

Conclusions

The experimental work showed that the damage to the aircraft structure depended upon the current and the current density at the fault. In all cases when the contact area between the cable and airplane structure was small the latter was perforated and the fault self-clearing irrespective of the ampere capacity of the systems tested. Although in the majority of cases the extent of the perforation was insufficient to weaken the airplane members, similar short circuits occurring on the oil or gasoline lines would probably result in serious damage from fire. Fire may also occur if molten aluminum-alloy particles, scattered as a result of a short circuit as previously mentioned, should fall on inflammable material within the airplane.

When the pressure between the conductor and airplane structure was increased, and the contact area thus enlarged, the short circuit was continuous, and at times a weld was produced. The pressure required for such a sustained short circuit was dependent upon the ampere capacity of the electic systems. From this type of short circuit serious damage to the generating system is conceivable unless the fault is cleared by suitable circuit protective apparatus.

On the 28.5-volt d-c system, of a total of 70 contacts applied with small contact area, all resulted in the fault being self-clearing; of a total of 30 contacts applied with increased pressure, 26 resulted in a weld or a continuance of the short circuit without arc or weld, while the remaining four burned clear. The division of results on the a-c and 120-volt d-c systems was somewhat the same. In the high-altitude-pressure tests the results were practically the same as obtained at sea-level pressure. With a light contact at the short-circuit area the fault burned clear and, because of less oxidation, the resulting perforation was somewhat more clean-cut than that produced at atmospheric pressure. Increase in contact pressure resulted in sustained short circuits as before.

Vibration of the aircraft structure increases the duration of a fault and the resulting damage to the aircraft structure. When only four generators formed the 28.5-volt d-c power system, the pressure required on the conductor to produce a weld was much less than when one, two,

Figure 9. Damage to aircraft structure and cable from 50-caliber-machine-gun bullets

Range: 80 yards. Resulting electric-fault damage shown at *A* where weld took place

Electrically Driven Gyroscopes for Aircraft

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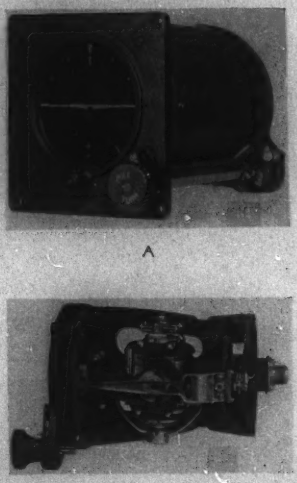
GYROSCOPIC instruments are given a place of prominence on the instrument panels of military and commercial aircraft. They are among the "most used" of all the instruments and are necessary for blind flight since they serve as stable references in space when natural objects are not visible. This group consists of a gyro horizon, showing the attitude of the aircraft—that is, whether or not it is in level flight; a directional gyro, which shows departure from course; and a bank and turn indicator, indicating rate of turn.

Operating Principles of Gyroscopic Instruments

Regardless of the type of power used, the gyroscopic principle and general construction of these instruments are as outlined hereinafter.

The gyro horizon (Figure 1) consists of a spinning rotor with its shaft mounted vertically in a gimbal which is pivoted athwartships to another gimbal. This outer gimbal is in turn pivoted fore and aft to the main frame of the instrument. The axis of the rotor is mechanically free to tilt in any direction with respect to the instrument case and by means of a bar and pointer relative motion of the rotor axis, and the case is indicated on a dial. Since the spinning rotor tends to stay vertical, the bar and pointer show movement of the instrument case, or the aircraft, with respect to a fixed vertical.



A

B

Figure 1. Gyro horizon indicator

In the side view the cover and casing mechanism are removed to show the gyroscope

The significance of the position of the bar and pointer is shown in Figure 2.

In the directional gyroscope, the spin axis of the rotor is horizontal. The motor frame, or gimbal, is pivoted horizontally to an outer gimbal, and this is pivoted vertically to the main frame. A gear attached to the vertical gimbal drives a dial, calibrated in degrees, through a 1 to 1 ratio, and since the spinning rotor and its gimbal tend to stay in a fixed position in space, movement of the instrument case (or of the aircraft) around its vertical axis will cause rotation of the dial (see Figure 3). Any departure of the plane from a fixed course will be indicated by movement of the dial with respect to its index.

The gyroscope of the bank and turn indicator consists of a spinning rotor with its shaft athwartships and its bearings in a frame or gimbal which in turn is pivoted fore and aft to the instrument frame. The gimbal and rotor assembly is restrained by a spring and a pointer is mechanically linked to the gimbal to show direction and magnitude of its movement (see Figure 4).

The spinning rotor tends to maintain its position in space, but if torque is applied in the plane of the rotor axis precession will occur, that is, the rotor will tilt in a plane 90 degrees from that of the applied torque. The tilt will be in the direction to make the spin axis of the rotor coincide with the axis of the applied torque. Turning of the aeroplane thus causes precession, and movement of the pointer shows direction and rate of turn (degrees per minute). A ball bank indicator, consisting of a ball in a liquid filled curved glass tube, is set into the face of the instrument.

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or three batteries were added to the circuit, the pressure difference increasing successively with each addition. With the generators operating under load conditions the fault short-circuits most of the load and the burning-clear phenomenon is, in general, as before. The effect of increasing the short-circuit resistance is similar to reducing the ampere capacity of the electrical system and the contact pressure necessary for producing a sustained short circuit is reduced. Thus faults occurring in sections of the circuit remote from the generating system will require less pressure to produce a weld than those occurring near a bus. Although an increase in system ampere capacity reduces the hazard from a weld-in type of short circuit, this may not be the case for short circuits which are self-clearing. In these cases the danger from fire will be greater and the short-circuit damage to a highly stressed member may be such as to cause collapse of that member.

The minimum current, of the series of d-c tests, causing damage to an airplane section was 1,100 amperes, the fault clearing after 0.74 second. The minimum time for damage was 0.05 second with a maximum peak current value of 3,420 amperes. Current values ranged as high as 4,500 amperes, and some short circuits carrying such currents did not burn clear until after two seconds' duration.

In the a-c tests, the current level was limited, and for a maximum value of 2,150 amperes the fault cleared in 0.035 second. This was also the minimum time of short circuit for a size 1/0 cable which was the type used throughout the d-c tests.

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Operational Requirements

Instruments, such as described previously, have been in common use for many years. These have been air driven and have performed quite satisfactorily under usual peacetime flight conditions. Limitations of air operation at extreme altitudes and temperatures experienced in combat can be removed, and other advantages obtained, by electric drive. The trend toward complete electrification of aircraft also makes electrification of these instruments desirable.

The general requirements for such instruments are as follows:

1. Reliable and accurate performance from plus 70 to minus 54 degrees centigrade and at all altitudes to 40,000 feet.
2. Quick starting.
3. Operation in excess of 1,000 hours without servicing.
4. Small size and light weight.
5. Accessibility of parts for servicing.
6. Protection from dust and harmful fumes.
7. Ability to withstand vibration and shock.

Power Supply

The selection of the type of power to be used for electrically driven gyroscopes is influenced by factors of convenience and performance. Low-voltage direct current is universally available on aircraft and would be desirable from the standpoint of application. However, the problems of commutation at high speeds and high altitudes make it impractical for sensitive instruments.

The gyro horizon and the directional gyro are essentially free gyroscopes, very sensitive to balance and bearing friction. High speed is essential for stability, and the products of brush and commutator wear would rapidly affect the performance of these devices and make frequent cleaning and servicing necessary.

A 115-volt three-phase 400-cycle power supply was chosen for these instruments since this is now available on many planes or can be made available by the installation of an inverter. Polyphase is preferable to single phase from the standpoint of simplicity of motor design and starting characteristics.

The bank and turn indicator does not require the same degree of refinement mechanically or gyroscopically as the other instruments, since it is not a free gyro and indicates short-time departures from normal. A 5,000 rpm centrifugally regulated direct-current motor is satisfactory for this device. The design details of the bank and turn indicator are not within the scope of this paper, which deals primarily with the application of electricity to the operation of the gyro horizon and the directional gyro.

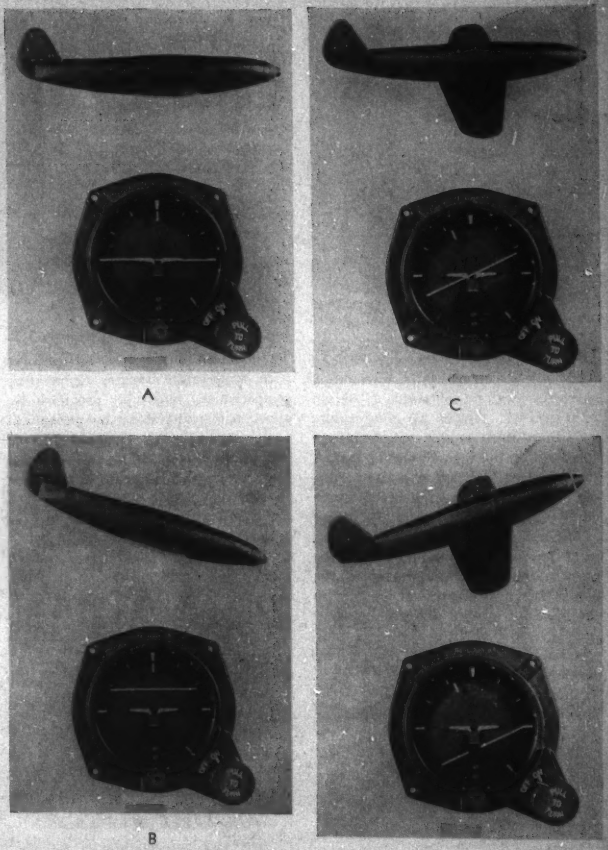

Figure 2. Appearance of gyro horizon dial for various attitudes of the aircraft

The wings represent the plane on which the instrument is installed, the bar the horizon

A-C Motor Design

Any gyroscope has rigidity by virtue of its rotor speed and the radius of gyration of its spinning mass, the latter factor being a squared function. Since dimensional and weight limitation of the instruments fix the weight of the rotor at approximately one pound, it is necessary to use as high a speed as possible consistent with long life, and to concentrate the weight at its outermost diameter. This latter requirement led to an umbrella-style rotor with the driving element within.

A hysteresis type of motor was chosen since it has good starting characteristics, runs at synchronous speed, and makes possible a symmetrical rotor with all smooth surfaces which can be manufactured with inherently good balance. The rotor consists of a bronze cup with rings of magnet steel spun in and ground internally for concentricity and accurate diameter. The rotor assembly must be precisely balanced for good instrument operation as well as life.

The stator is wound for four poles,

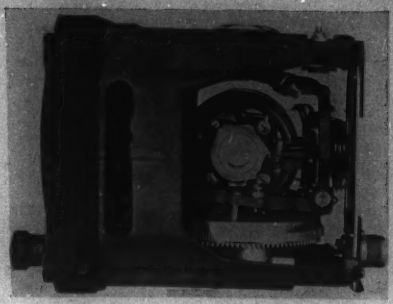

Figure 3. Directional gyro indicator

In the side view the cover is removed to show the gyroscope

Figure 3A is shown at the left, 3B at the right

fixing the speed at 12,000 rpm. With an input of less than ten watts, acceleration characteristics are obtained as shown in Figure 5. Under all temperature conditions these motors will be up to speed within the engine warm-up period, thus assuring safe performance at take-off. Figure 6 shows the speed-torque curve of the motor.

The useful life of a gyroscopic instrument has usually been limited by the rotor bearings. In addition to speed, the factors affecting life are unit pressure on the bearing surfaces, lubrication, dimensional accuracy, and cleanliness.

A cross-sectional view of the bearing developed for the gyro motor is shown in Figure 7. The unit pressures on the shaft pivot are kept at a minimum by forming it to a radius just slightly greater than the radius of the ball. The ball race is ground and lapped to a spherical form so that the ball track remains circular even though the center lines of the race and shaft do not exactly coincide. The contour and finish of the ball track in both the shaft and race are manufactured to exacting standards. Balls are matched for diameter and checked for sphericity within 25 millionths of an inch. Parts are cleaned and assembled in an air-conditioned area to insure absolute cleanliness.

The high torque of the motor makes it possible to use a generous amount of high quality lubricant in each bearing with reservoir pads back of the ball race. With electric drive, the instrument case may be sealed against dust and fumes which might contaminate the bearing lubricant. There is no flow of air through the case to pull out the lubricant at high temperatures. Life tests indicate well over 1,000 hours' operation without servicing.

Bearing adjustment is extremely critical, and for good operation cannot vary more than 0.0001 inch from optimum. To maintain this precise setting over wide temperature ranges, temperature compensation must be provided by selection of materials or by mechanical compensating means. Good results have been obtained by matching the expansion characteristics of the materials used for the shaft and gimbal.

Figure 4. Bank and turn indicator

The ball bank indicator beneath the gyro-actuated pointer serves to indicate the proper angle of bank for any rate of turn

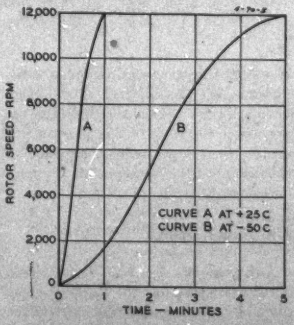

Figure 5. Acceleration curves of 115-volt 400-cycle three-phase motor for gyroscopic instruments

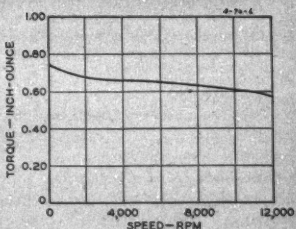

Figure 6. Torque-speed curve, 115-volt 400-cycle three-phase motor for gyroscopic instruments

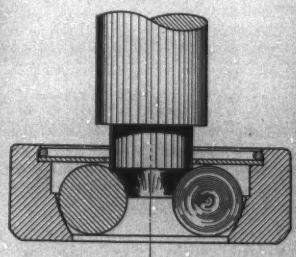

Figure 7. Cross section of bearing for gyro motor

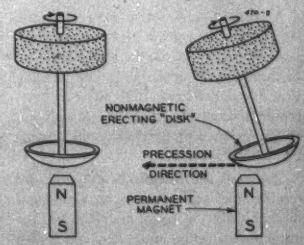

Figure 8. Schematic sketch showing arrangement of erecting device for gyro horizon

Gimbal Bearings

The requirements for gimbal bearings are just as exacting as for motor bearings but with more emphasis on sensitivity and less on ability to stand up under severe service. The bearing commonly used in existing gyroscopic instruments was found to be satisfactory for this application.

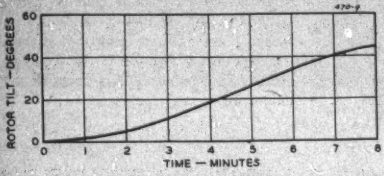

Figure 9. Erection characteristics of gyro horizon

Various tilt angles up to 45 degrees have been plotted against the time in which the erection device returns the axis of rotation to a true vertical

Accuracy of dimension and cleanliness are just as critical as for the motor bearing, and alignment of bearing race and pivot must be held to extremely close tolerances.

In the assembly of the motor and gimbals, each unit subassembly must be accurately balanced. Unbalanced torque about any axis will cause error in indication. Bearings must be set with no end shake to avoid shifting weight. Materials must be selected to avoid change in bearing adjustment or shifting of the center of gravity of any subassembly with changing temperature.

Coupled with the necessity for no end shake of bearings is the equally important requirement of minimum friction. Friction in the gimbal bearings causes inconsistency in the indication of the gyro horizon and drift in the directional gyro.

Power Leadins

The method of getting power to the motor through the gimbals presented some difficulties, since any extraneous torques or frictions are detrimental to the functioning of the instrument. Movable contacts add friction of too great magnitude and the probability of variable friction. Flexible leads or pigtails introduce variable torques or forces as well as insulation hazards. Small instrument-type spirals, while not ideal from the standpoint of space requirements, have low uniform torque, no friction, and can be well insulated. These have proved to be quite satisfactory, and by assembling them to have zero torque at the normal operating positions their effect on the accuracy of the instruments is negligible.

Slip rings and brushes are used on the vertical gimbal of the directional gyro, since it must have unlimited freedom of movement on this axis. The effects of friction on this axis will usually balance out so long as it is uniform and equal in both directions.

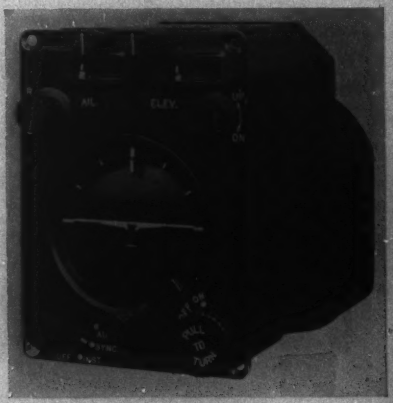

Figure 10. Directional gyro and gyro horizon equipped with pick-offs, potentiometer controls, and synchronizing indicators to serve as the "brains" of an automatic pilot

Figure 10A is shown at the left, 10B at the right

Gyro Horizon-Erection System

Since the motor shaft of the gyro horizon is normally vertical, gravity may be utilized to apply a correcting force when it is not in a vertical position. Such an erecting device serves to maintain the rotor in a vertical position over long periods of time and to bring it back to vertical should it be upset or started in a nonvertical position.

Erection in air-driven instruments is accomplished by means of gravity-actuated valves controlling four air streams which supply the correcting forces. This method is, however, subject to decreased effectiveness with increased altitude and would require additional auxiliary equipment if applied to the electrically operated devices. A unique application of permanent magnetism, therefore, has been developed to accomplish this function without the use of auxiliaries.

This erecting device consists of a pendulum free in two axes and carrying a small permanent magnet in close relation with a copper-alloy disk attached to the lower end of the motor shaft. When the motor shaft is vertical, the magnet, under normal conditions, is suspended at the center of the spinning disk, and no unbalanced force results from the damping effect of the magnet on the disk (see Figure 8). However, if the rotor is tilted from vertical, the magnet exerts a force on the spinning disk in a direction to cause precession toward the true vertical.

The rate of correction is made low enough, so that random accelerations of the aircraft are averaged out in normal flight. In turns, however, the angular acceleration causes the magnet to swing out and pull the rotor off vertical. No simple way has been found to eliminate this turn error due to the erecting device, but compensation can be made for 180-degree turns at one rate of turn. Practice has established 180 degrees per minute as the standard rate, and compensation is accomplished by tilting the motor

shaft forward a few degrees from vertical, the exact angle being determined by the erection rate.

Use and Characteristics of the Directional Gyro

The directional gyro and magnetic compass are supplementary instruments in that the compass indicates direction but is subject to turning errors and instability in rough air, while the directional gyro maintains a set course in a deadbeat manner. In practice, the directional gyro is used to hold course, but it is periodically checked against the magnetic compass and reset as required.

Since the gyroscope tends to stay in the position set, the perfect instrument will show drift because of the rotation of the earth. The magnitude of this drift varies with latitude. It would be zero at the equator where the rotor shaft is parallel to the earth's axis, and 15 degrees per hour at the poles where the rotor shaft is 90 degrees from the axis of the earth. Correction can be made for a given latitude, as for example 45 degrees north, but the error is then doubled at 45 degrees south latitude. Correction is made by moving a small adjusting weight, and it is not difficult to change the setting to obtain compensation for the latitude in which the instrument is to be used.

The directional gyro is equipped with an antitumbling device which maintains the gyro motor in a perpendicular relationship with the vertical gimbal so as to set up a maximum of safe operating range available for maneuvering of the aircraft. In the electrical design, a simple means is employed. Gyroscopic theory dictates that torque about one axis of a gyro normally produces precession about a perpendicular axis; however, if that precession is resisted, the precession is reflected back into the axis initiating the torque. By properly balancing the centering torque contributed by the spirals about the motor axis, and the counterfriction torque about the vertical axis, the perpendicular relationship between the motor and vertical gimbal may be maintained.

Caging Mechanism

Both the horizon gyro and directional gyro are equipped with caging mechanisms to hold the delicate gyro elements to prevent damage resulting from acrobatics of the aircraft beyond the limits of freedom of the devices. The caging mechanisms also allow the pilot to reset the instrument to its normal operating position. In the case of the gyro horizon, the pilot may level his aircraft and uncage instrument, saving the erection time necessary for it to restore itself. In the case of the directional, the pilot, by caging and turning the caging knob, may rotate the gyro element to any position of reference he desires.

Adaptability to Control

Electrically driven gyros lend themselves conveniently to interconnection for automatic control such as required in the automatic pilot. Figure 10 illustrates a gyro horizon and a directional gyro which have been equipped with induction-type pick-offs for this purpose. It was possible to incorporate into the instruments themselves the necessary controls and indicators for synchronizing and adjusting trim and sensitivity.

Conclusion

Electricity has brought to small gyroscopic instruments increased reliability and improved accuracy under extremes of temperature and altitude. It permits sealing of the case to protect the sensitive mechanism from dirt and corrosive fumes and thus prolongs the life of the instrument by preventing bearing wear due to grit or loss of lubrication. The ability to remove the cover with the operating mechanism intact aids in locating trouble and simplifies overhaul and adjustment.

The present trend is toward complete electrification of aircraft, eliminating, to a large extent, the pneumatic and hydraulic systems now commonly used. Electrification of the gyroscopic instruments is a necessary part of this program.

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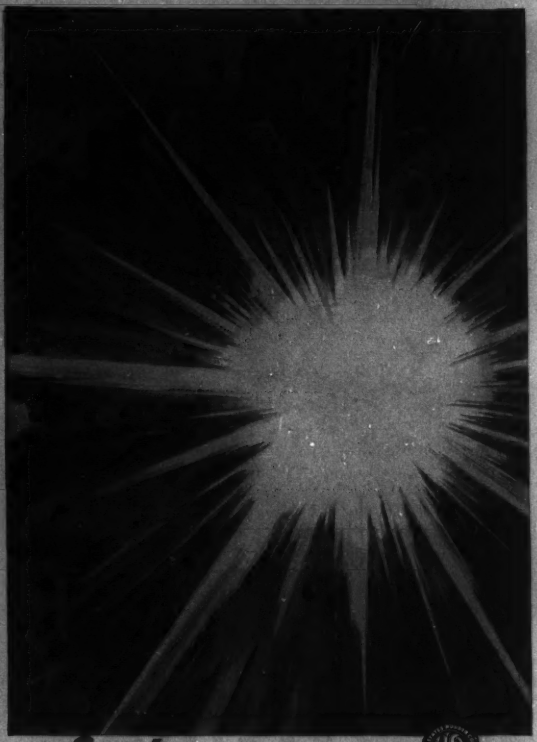

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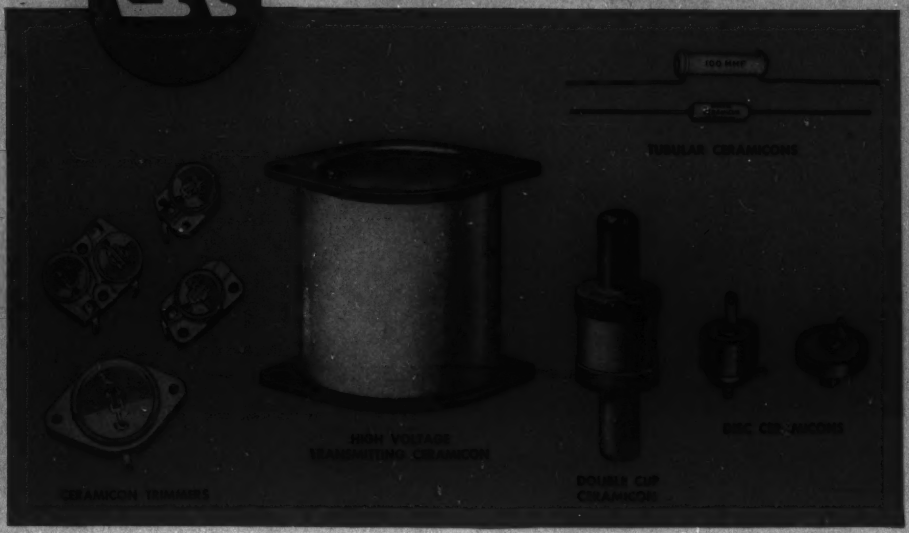

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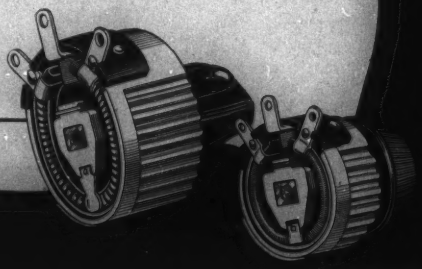

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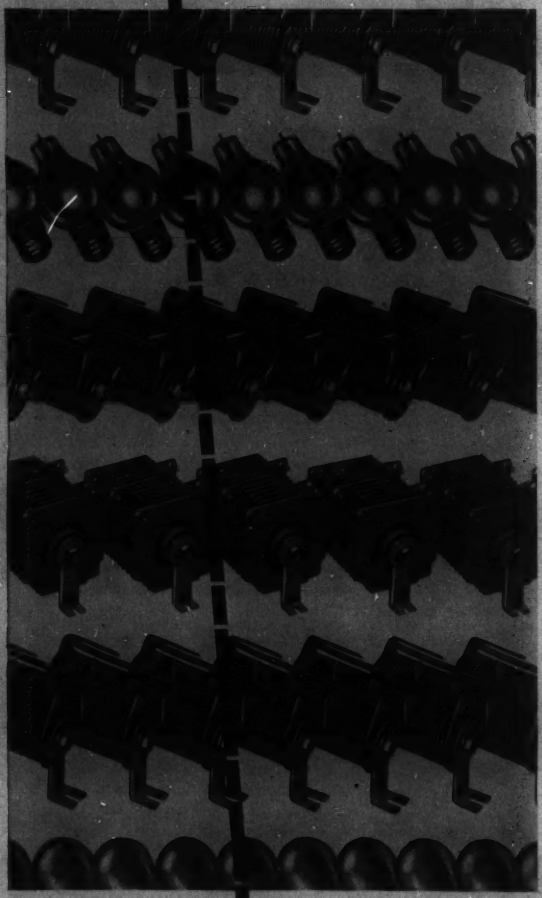

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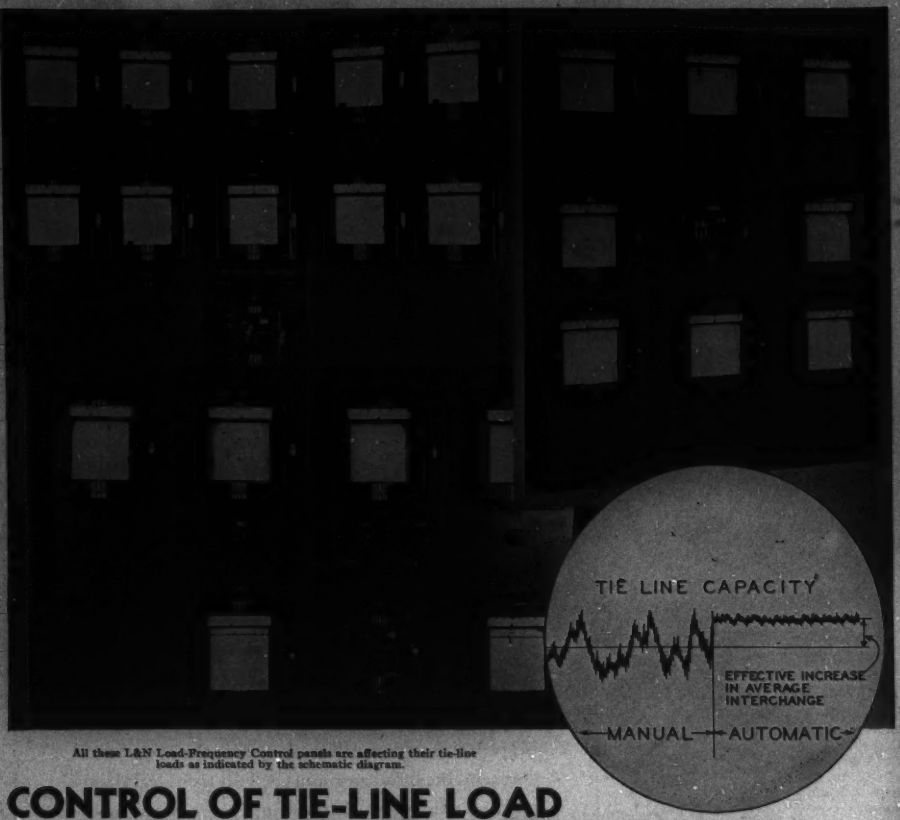


All these L&N Load-Frequency Control panels are affecting their tie-line loads as indicated by the schematic diagram.

CONTROL OF TIE-LINE LOAD IS LIKE "FINDING" A GENERATOR

The effective carrying capacity of a tie-line is increased, instantly and permanently, when the switches are thrown to turn load-frequency regulation over to the appropriate battery of L&N instruments.

There's no mystery about how the result is achieved; it's simply because all significant facts concerning interchanges and outputs are telemetered to the system-regulating point or points, where the fully-automatic instruments are fast, sensitive and accurate enough to execute the dispatchers' wishes more closely than men could execute them. The average of tie-line load rises toward the line's capacity; the line carries more load; the effect is the same as though another generator has been found and put to work.

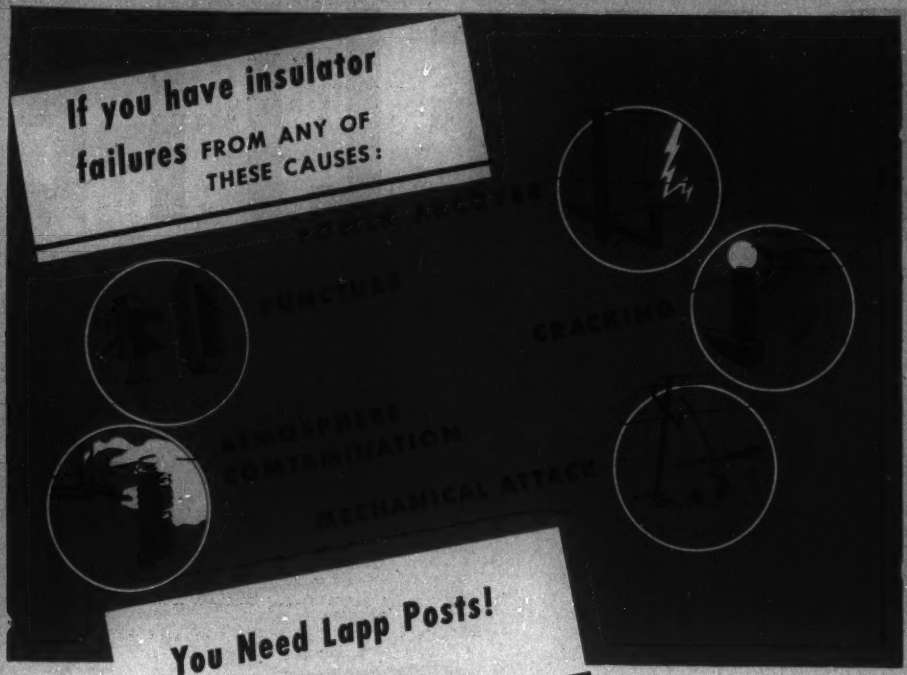
And this is not only in isolated cases; it is being attained in war-busy power centers all over the country. We show above just a few of the panels we have recently supplied for this service; each designed after conference with the operating engineers concerned; each built to help that one network carry its load more effectively.

For a description of the equipments, see Technical Publication N-56-161(1). For data on a specific problem, please write outlining the situation.

Jrl Ad N-56-161(4)

depends on me!
A Slogan For Every American

LEEDS & NORTHRUP COMPANY, 4902 STENTON AVE., PHILA. 44, PA.
LEEDS & NORTHRUP
MEASURING INSTRUMENTS · TELEMETERS · AUTOMATIC CONTROLS · HEAT-TREATING FURNACES



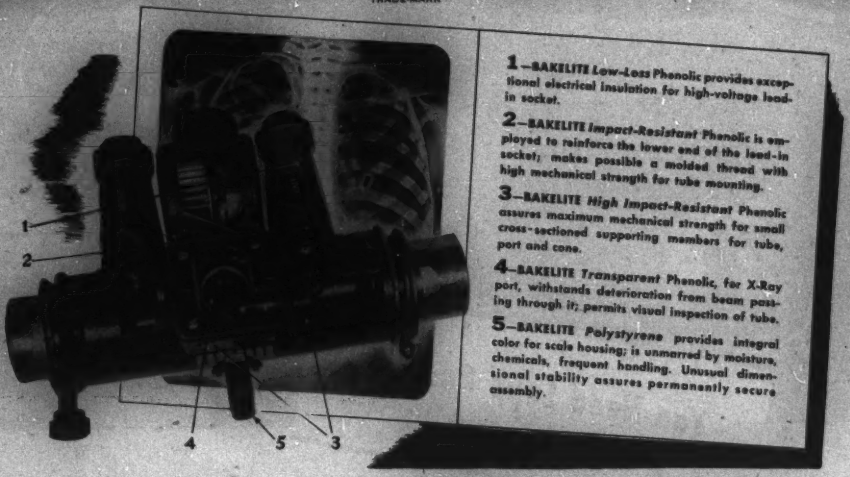
• Looked at from a dollars-and-cents viewpoint—or in terms of man-hours of under-staffed and over-worked patrol and maintenance crews—Lapp Line Posts and Station Posts are smart business. For the engineering achievement of these insulators—now proved by more than 12 years of service in the toughest areas—is that of eliminating at their source *all* the common causes of high-voltage insulator failure. A one-piece post body, with multiple short rugged petticoats, this Lapp design is proof against puncture and cracking, is capable of withstanding enormous shock from power arcover or mechanical attack, provides uniform leakage path for operation under dirt conditions. For replacement, new construction or line conversion, Lapp Posts on your transmission lines and substations will give better performance and less trouble.

Lapp

LAPP INSULATOR COMPANY, INC., LE ROY, N. Y.

BAKELITE

TRADE-MARK


1
2
4
5
3
1—BAKELITE Low-Loss Phenolic provides exceptional electrical insulation for high-voltage lead-in socket.
2—BAKELITE Impact-Resistant Phenolic is employed to reinforce the lower end of the lead-in socket; makes possible a molded thread with high mechanical strength for tube mounting.
3—BAKELITE High Impact-Resistant Phenolic assures maximum mechanical strength for small cross-sectioned supporting members for tube, port and cone.
4—BAKELITE Transparent Phenolic, for X-Ray port, withstands deterioration from beam passing through it; permits visual inspection of tube.
5—BAKELITE Polystyrene provides integral color for scale housing; is unmarred by moisture, chemicals, frequent handling. Unusual dimensional stability assures permanently secure assembly.

FIVE DIFFERENT PLASTICS *SO THAT HIGH-VOLTAGE X RAY CAN SAVE SOLDIERS' LIVES*

The manufacture of this X-Ray tubehead called for the solution of many problems involving other than electrical properties. In addition to high voltage, the problems of deterioration from X Rays, of impact and vibration, temperature extremes, corrosion and transparency had to be solved—in a product whose complex parts must be made at high speed.

For the parts indicated above, the right BAKELITE Plastic solved each problem in turn. The tubehead, part of a mobile unit made by Picker X-Ray Corporation, New York, for the armed forces, is literally a "miniature catalog" of BAKELITE Plastics, each carefully selected for its individual properties—and adaptable to extremely rapid fabrication into finished parts.

A thorough knowledge of BAKELITE Molding Plastics will show you that there is a right plastic for every electrical application. Close teamwork of manufacturer, fabricator, and BAKELITE Plastics Headquarters will eliminate errors and save valuable time. Let our Field Engineers work with you on your essential products, or write for Booklet 5-P, "A Simplified Guide To Bakelite Plastics."

BAKELITE CORPORATION, 30 E. 42 St., New York 17

Unit of Union Carbide and Carbon Corporation

UCC

Molding Plastics

"SWINGING BUS" *proves highly satisfactory*

They're war workers, these Alcoa Aluminum buses, carrying power for vital production. Suspended from standard power-line insulators, with spans 24 feet rather than the usual 8 feet, costs were much lower than for rigid bus bar construction.

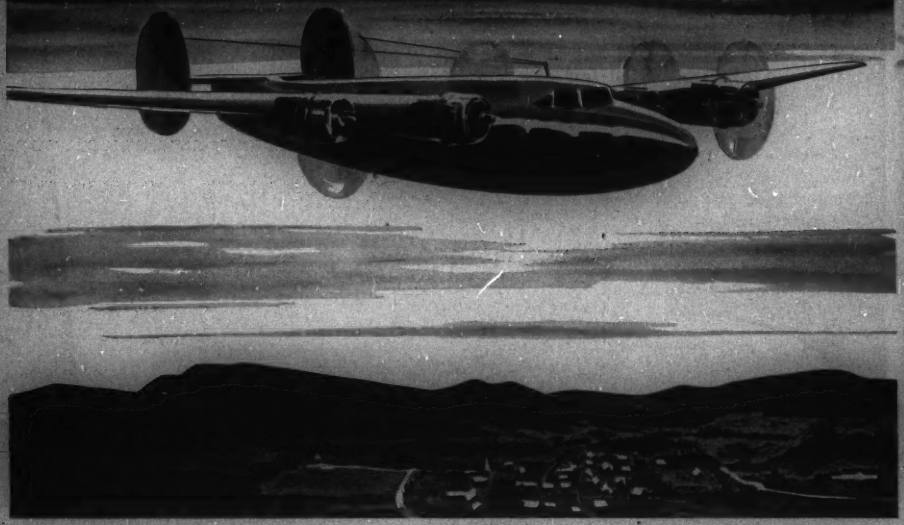
Buses are free to swing. The stiffness of the two Alcoa Aluminum channels comprising each conductor permits this long span design. The standard lengths supplied by Alcoa were welded at the joints to make each run a solid unit. The aluminum supplies the high electrical conductivity required.

Alcoa bus bars, Aluminum Cable Steel Reinforced, and fittings are available for essential work. If your power project has been approved, Alcoa can supply the necessary materials. With them, of course, goes the usual Alcoa engineering advisory service. ALUMINUM COMPANY OF AMERICA, 2149 Gulf Building, Pittsburgh 19, Pa.

Note to manufacturers of electrical equipment: W.P.B. Order M-1-l now permits the use of aluminum for electrical conductors.

ALCOA
ALUMINUM

Ceiling—Unlimited



The war, although treacherous, has brought about the development of many new devices. Surely, it can be said "Ceiling Unlimited" for what is in store in the electrical industry is beyond comprehension of the average man today.

Research in the field of insulating varnish has kept pace with the development of newer electrical equipment. The trend today has been toward faster curing varnishes which have exceptionally long life and yet possess a certain degree of flexibility.

The JOHN C. DOLPH COMPANY for over a third of a century has specialized only in the manufacture of insulating varnishes and are directly responsible for many of the improvements made in this field. Yesterday, today and tomorrow, you will find that DOLPH'S Insulating Varnishes meet the exacting needs of the electrical industry.

Perhaps you do not know just what type of varnish to specify for treatment of your newly designed units. It is a very complex problem for varnish insulation and treatment which may prove very successful for one type of an electrical unit may be entirely unsatisfactory for another.

We maintain a fully equipped Laboratory for those who are confronted with an insulating varnish problem. We are confident, no matter what your problem may be, that with our years of research and specialization in the field of insulating varnishes, we can help you. There are no obligations, so why not let us assist you?

Dolph's

JOHN C. DOLPH COMPANY

Insulating Varnish Specialists

166-8 Emmett St. Newark 5, N. J.

WORLD FAMOUS OSCILLOSCOPES by DUMONT

Use Capacitors by INDUSTRIAL CONDENSER CORP.

Capacitors used in Dumont's famous oscilloscopes are especially designed, engineered and manufactured for unusual performance under difficult operating conditions.

PAPER, OIL AND ELECTROLYTIC CAPACITORS

INDUSTRIAL CONDENSER CORPORATION

1725 W. NORTH AVE. CHICAGO 22, U.S.A.

Specialists for over a generation in

OIL IMMERSED MOTOR CONTROL

ROWAN CONTROL

THE ROWAN CONTROLLER CO., BALTIMORE, MD.

NOW more than ever

protect men and equipment!

use the

Statiscope

FOR A.C.

and KNOW that circuits are alive or dead

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Write for Descriptive Circular

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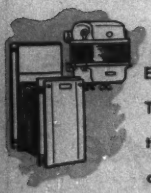
MINERALLAC ELECTRIC COMPANY

25 N. Peoria St. CHICAGO, ILL.

50 Church St. NEW YORK CITY

ON THE JOB...

AMERTRAN
DRY-TYPE
TRANSFORMERS



Even in crowded load centers, AmerTran Dry Type Transformers are out of the way. Light, compact and smoothly contoured, they may be tucked into pillars or mounted overhead on I beams if necessary. They are made in a wide variety of ratings, and where ambient or operating conditions require, Class B insulation may be specified.

If you are looking for more than the usual advantages* from transformers at load centers, you have an additional reason for investigating AmerTran Dry Type Transformers. These units are used for insulating circuits, balancing loads, boosting line voltages, and in many other special applications. Complete information covering standard and special AmerTran Dry Type Transformers for indoor and outdoor location will be sent upon request.

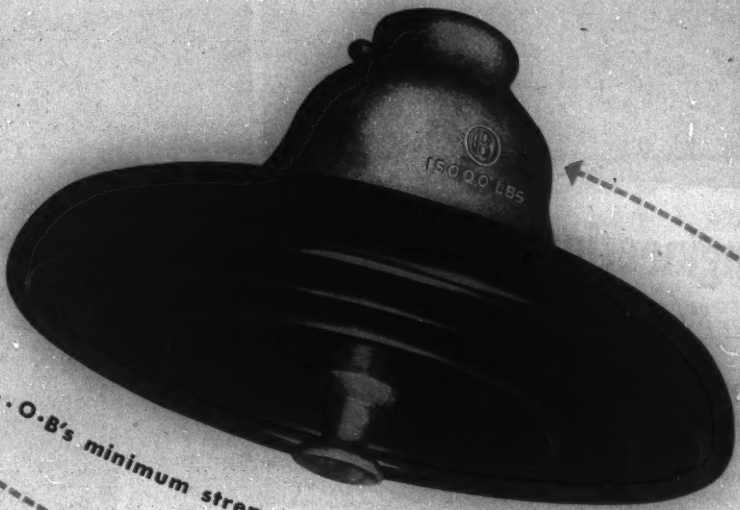
AMERICAN TRANSFORMER COMPANY
178 Emmet Street, Newark 5, New Jersey

* Saving copper, reducing line losses, obtaining improved voltage regulation or added load flexibility.

Pioneer Manufacturers of Transformers, Reactors and Rectifiers for Electronics and Power Transmission

AMERTRAN

THE KIND OF STRENGTH THAT COUNTS
BECAUSE YOU CAN COUNT ON IT!



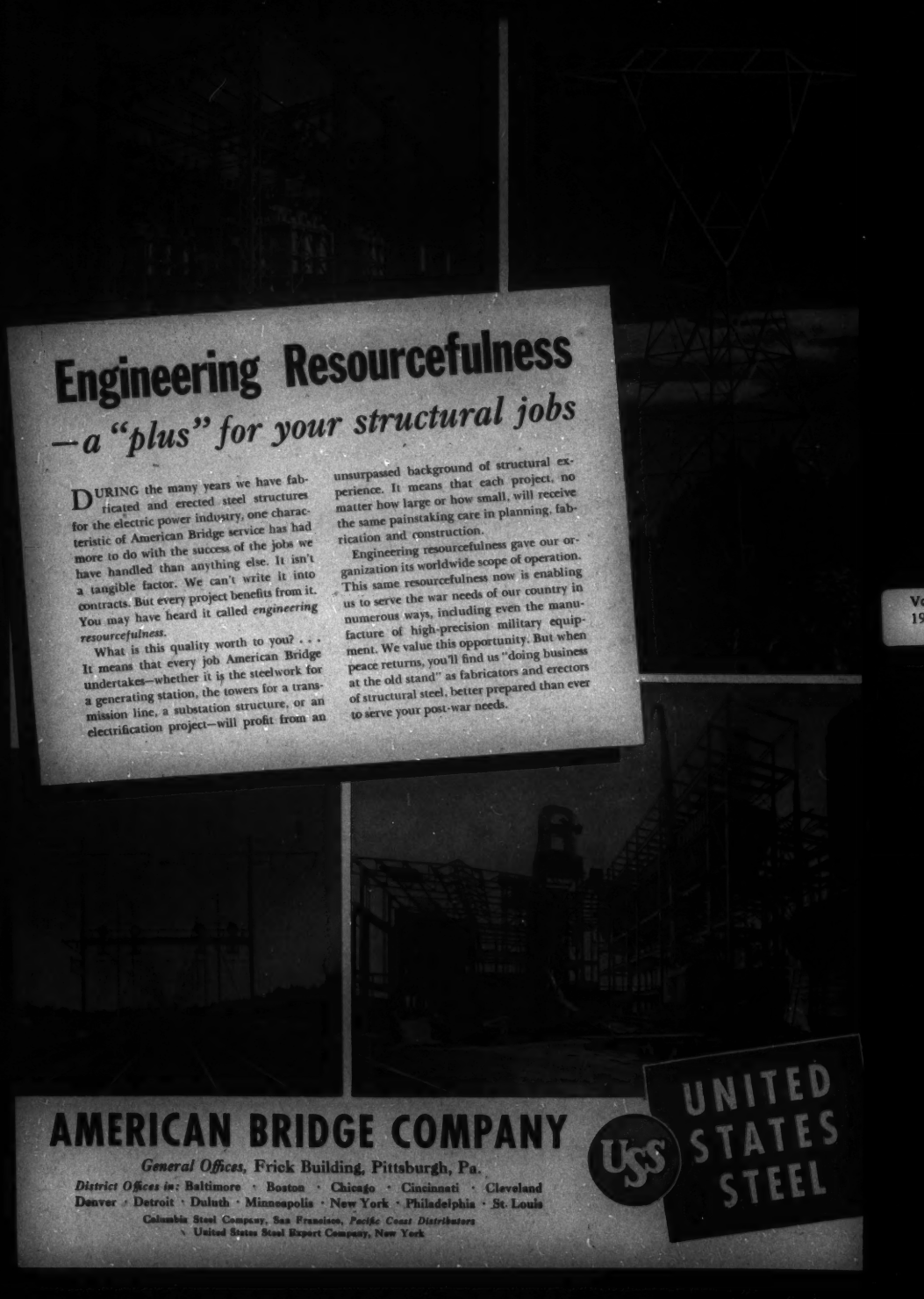
...O-B's minimum strength rating of Suspension Insulators

Electrically, all good makes of suspension insulators are highly standardized. The "frontier" of insulator development today is along lines of mechanical strength. The problem is not one of brute strength so much as it is one of consistent, reliable strength...Higher mechanical factors introduce the greater possibility of deviation. Average strength--the basis on which such insulators were rated--covered this range of variation, and left the transmission engineer in the dark with no specific value to build on. He usually called for over-strength and paid a premium for it, just to be sure of getting what he needed...O-B's superior manufacturing methods enabled it to be the first to offer suspension insulators rated on the basis of specific *minimum strength*--the starting point of any good engineering design. This value is permanently cast on every cap. It is a definite rating of each individual insulator. Look for it. Get the kind of strength that *counts*, because you can *count* on it!

Ohio Brass

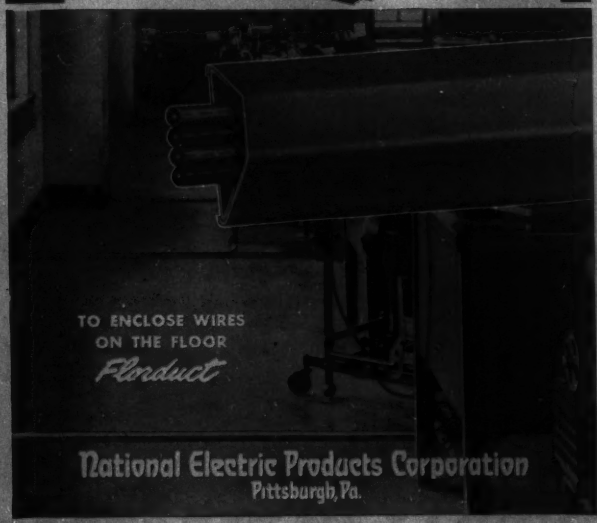
MANSFIELD, OHIO

467-H CANADIAN OHIO BRASS CO., LTD., NIAGARA FALLS, ONT.


Engineering Resourcefulness
—a "plus" for your structural jobs
DURING the many years we have fabricated and erected steel structures for the electric power industry, one characteristic of American Bridge service has had more to do with the success of the jobs we have handled than anything else. It isn't a tangible factor. We can't write it into contracts. But every project benefits from it. You may have heard it called *engineering resourcefulness.*
What is this quality worth to you? . . . It means that every job American Bridge undertakes—whether it is the steelwork for a generating station, the towers for a transmission line, a substation structure, or an electrification project—will profit from an unsurpassed background of structural experience. It means that each project, no matter how large or how small, will receive the same painstaking care in planning, fabrication and construction.
Engineering resourcefulness gave our organization its worldwide scope of operation. This same resourcefulness now is enabling us to serve the war needs of our country in numerous ways, including even the manufacture of high-precision military equipment. We value this opportunity. But when peace returns, you'll find us "doing business at the old stand" as fabricators and erectors of structural steel, better prepared than ever to serve your post-war needs.
AMERICAN BRIDGE COMPANY
General Offices, Frick Building, Pittsburgh, Pa.
District Offices in: Baltimore · Boston · Chicago · Cincinnati · Cleveland
Denver · Detroit · Duluth · Minneapolis · New York · Philadelphia · St. Louis
Columbia Steel Company, San Francisco, *Pacific Coast Distributors*
United States Steel Export Company, New York
USS
UNITED STATES STEEL

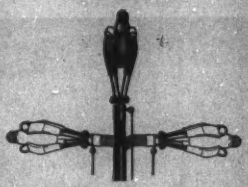
FITTINGS
for
NATIONAL ELECTRIC
Flonduct

KICK-PR
MOP-PR
STRONG
SAFE
APPROV



National Electric Products Corporation
Pittsburgh, Pa.

MATTHEWS HOLDFAST LAMP CHANGERS



Removes and replaces lamps in high places, such as ceilings, side walls, electric signs, etc. Like a human hand on the end of a wooden pole. Saves time and prevents ladder accidents.

To remove or replace lamps from side walls or at an angle, pull cord attached to the swivelled ring. This bends the wristlike coil spring so that the Changer will work just as well at a right angle to the rotating pole as in vertical position.

Shipping weight each, 1 pound.

No. 2

For 50-Watt Rough Service, 15 to 100 Watt Mazda and other lamps up to 3 inches in diameter.

No. 2	Less Than 6	6 to 11	12 or More
Price Each	$5.00	$4.75	$4.50

No. 3

For 60 to 500 Watt Mazda Lamps and other large and odd shapes up to 5 inches in diameter.

No. 3	Less Than 6	6 to 11	12 or More
Price Each	$5.50	$5.25	$5.00

All Prices F.O.B. St. Louis, Mo.

Specially treated wood handles can be furnished in 6-foot sections at $3.75 per section including couplings.

Your Electrical Supply Jobber Will Fill Your Order.

W. N. MATTHEWS CORPORATION
ST. LOUIS, U. S. A.

YOUR BEST SIGNAL CIRCUIT IS THE POWER LINE ITSELF

VOICE—RELAYING—LOAD CONTROL dependably and economically with G-E CARRIER-CURRENT Equipment

CARRIER CURRENT superimposed on existing power lines assures:

1. **An *all*-weather communication channel.**
2. **Better, quicker protection against faults.**
3. **More accurate and efficient control and indication of loads.**

Today hundreds of G-E carrier-current installations, large and small, are providing the above and other advantages for power companies throughout the nation.

Pilot Relaying. Transferred Tripping. Signaling. Telephony. Telemetering. Super-

GENERAL ELECTRIC

191-87

visory Control. Automatic Load Control. Line Sectionalizing Control. . . . Singly, in pairs, or in multiple combinations, these and other carrier functions may be installed to best fit the needs of your system.

G-E standardized panel-unit assemblies permit step-by-step additions to original installations. Compactly "packaged," carefully built, thoroughly proved, they are capable of performing many functions through few carrier channels—all over one transmission system.

With the highest manufacturing standards, and the know-how of 20 years of research and development, G. E. offers the surest control facilities for better power service to the community.

General Electric engineers are prepared to discuss your needs—TODAY. . . . *General Electric, Schenectady, New York.*

** Tune in "The World Today" every evening except Sunday at 6:45 E.W.T. over CBS. On Sunday listen to the G-E "All Girl Orchestra" at 10 P.M. E.W.T. over NBC.*

★ BACK THE ATTACK—BUY WAR BONDS! ★

GENERAL ELECTRIC HAS PLANNED AND BUILT MORE CARRIER-CURRENT EQUIPMENT THAN ALL OTHER MANUFACTURERS COMBINED

CARRIER CURRENT

THE NERVE NETWORK OF THE POWER SYSTEM

QUICK, ECONOMICAL POWER FACTOR CORRECTION

... at the Source

In many cases, it is simpler, cheaper, and more practical to solve power factor correction problems *at the source* i.e., at the motor or other equipment itself, rather than at the transformer bank—a fact that Sprague Box-Type Capacitors have proved throughout industry. These Capacitors are available in 230, 460, and 475 volts, for 1-, 2-, or 3-phase systems, and in sizes from 1 to 10 Kva in single units, or grouped into nearly any size or capacity. Thus, one standard, economical design can be applied universally to cover an extremely wide range of applications. Write for details, including a copy of the helpful booklet "Sprague Capacitors for Power Factor Correction".

SPRAGUE SPECIALTIES CO.
NORTH ADAMS, MASS.

ARMY E NAVY

SPRAGUE

CAPACITORS

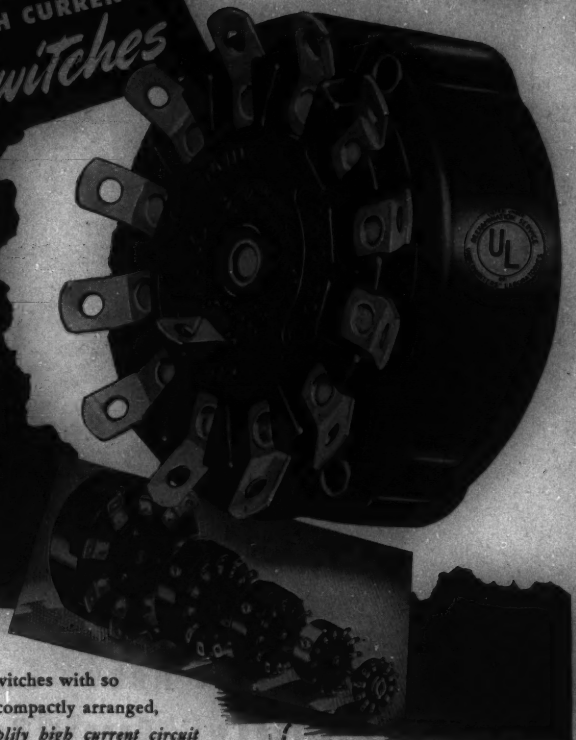
KOOLOHM RESISTORS

OHMITE

ALL CERAMIC, HIGH CURRENT

Tap Switches

SIMPLER
MORE COMPACT
HIGH CURRENT
CIRCUIT
SWITCHING



Never before have load-break switches with so many high current taps been so compactly arranged, yet perfectly insulated. They *simplify high current circuit switching* and provide greater operating convenience in a variety of applications. These non-shorting, single-pole, multi-point rotary selectors are made in 5 models, rated at 10, 15, 25, 50 and 100 amperes, 150, 300 volts A.C.—from 1¾" diam. to 6" diam.—with any number of taps up to 11, 12, 12, 12 and 8 respectively. May also be used on low voltage D.C. at reduced current ratings. Two or three units can be connected in tandem to form multi-pole assemblies. For full details, write for Tap Switch Bulletin.

Features

- ★ Ceramic Construction
- ★ Compact, All-Enclosed
- ★ Slow-Break, Quick-Make
- ★ Silver-to-Silver Contacts
- ★ Self-Cleaning Action
- ★ Low Contact Resistance
- ★ Cam & Roller Mechanism
- ★ High-Strength Ceramic Hub
- ★ Insulated Steel Shaft
- ★ Back-of-Panel Mounting

Send for Catalog and Engineering Manual No. 40

Write on company letterhead for your copy of this most complete, helpful guide in the selection and application of Rheostats, Resistors and Tap Switches.

OHMITE MANUFACTURING CO.
4801 WEST FLOURNOY STREET • CHICAGO 44, U.S.A.

VIBRATION in this Heavy Engine Foundation

Located and Analyzed with General Radio Vibration Meters

VIBRATION in this sugar-cane grinding tandem in the Florida Everglades was sufficiently serious to cause uneven settling of the heavy concrete foundation. The magnitude of the vibration depended upon the speed of one of the three Corliss engines driving the tandem, increasing as the speed increased.

MEASUREMENTS with the General Radio Vibration Meter and Analyzer showed that the frequency of the main component of the vibration corresponded to the single-mesh frequency of the main pinion on the engine. A speed-vibration characteristic, taken over the complete range of operating speeds, showed a pronounced resonance peak at 68 rpm, near top speed. Calculations confirmed the fact that the concrete foundation was in resonance at the gear mesh frequency corresponding to this speed.

ELIMINATION of the vibration was simple, once its nature and source were completely known. The cause was found to be poor gear alignment, resulting in worn gear teeth.

Most vibration problems encountered in industry are simple — when you know the answer. General Radio noise and vibration-measuring instruments are designed to get that answer for you quickly and accurately. Their theory and operation are completely described in "THE NOISE PRIMER." Write for your copy today. **Ask for Bulletin No. 866.**

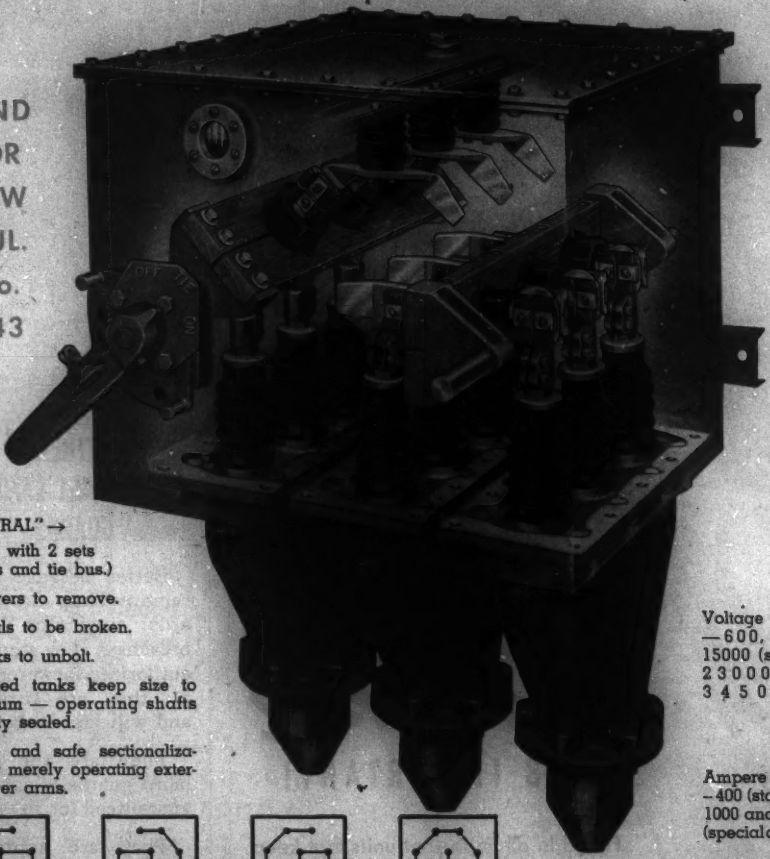
Because all of our facilities are devoted to war projects, this equipment is at present available only for war work.

GENERAL RADIO COMPANY Cambridge 39, Massachusetts

NEW YORK CHICAGO LOS ANGELES

QUICKLY ISOLATE *cable circuits with*
G & W TYPE "RA" OIL SWITCHES

SEND FOR NEW BUL. No. 743



TYPE "RAL" →
(3 way with 2 sets of links and tie bus.)

No covers to remove.

No seals to be broken.

No links to unbolt.

Oil filled tanks keep size to minimum — operating shafts perfectly sealed.

Simple and safe sectionalization by merely operating external lever arms.

Voltage ratings —600, 7500, 15000 (shown), 23000 and 34500 —

Ampere ratings —400 (standard), 1000 and higher (special designs)

FOUR CONNECTIONS WITH ONLY TWO SETS OF LINKS

Type "RAL" three way switch, with two sets of gang-operated links and one set of tie busses, makes an ideal unit for use on loop systems.

It permits the loop to feed through with or without the branch connected, also to feed the branch from either side with the other side disconnected. Thus, any section of the loop can be isolated and any branch can be disconnected without affecting the continuity of the loop. This situation formerly required the use of three separate oil switches, involving a greater expense not only of the switches but also in the additional manhole or vault space necessary.

Send for new bulletin No. 743

G&W ELECTRIC SPECIALTY CO.
Cable Terminating, Sectionalizing and Protecting Equipment
7700 DANTE AVENUE, CHICAGO 19, ILLINOIS, U.S.A.
Also made in Canada by Peterville Station, Ltd., Toronto

A

Choke

IS IMPORTANT!

Found in all important units that keep fighting men warned, informed and directed, are chokes.

Chicago Transformer has contributed many features of importance to their design, manufacture and improvement.

CHICAGO TRANSFORMER

DIVISION OF ESSEX WIRE CORPORATION

3501 WEST ADDISON STREET • CHICAGO, 18

MATTHEWS HOLDFAST LAMP GUARDS

Better because they remove lamp fire hazards; they stop lamp breakage; they stop unauthorized lamp removal; they are stronger and will last longer.

They are the only lamp guards which are guaranteed for 10 years.

They are approved by Fire Underwriters.

They are made in four sizes, of 14 bwg wire and for brass or weatherproof sockets.

Write for Bulletin A-B which will give you full details including net prices.

W. N. MATTHEWS CORPORATION

ST. LOUIS, U. S. A.

Compare LITTELFUSE with an ORDINARY FUSE

ORDINARY FUSE

1 Cap forced, or cemented on. Easily loosened.

2 No reinforcement. Blowing time not precise.

3 *Mechanically polarized.* Responds to vibration.

4 Unprotected against contraction and expansion.

LITTELFUSE

1 LOCKED CAP ASSEMBLY. Tube ends secure lock (Pat.). *No cement.*

2 Element twisted at 90° against severe vibration.

3 *Mechanically depolarized* against vibration.

4 "Gooseneck" takes up expansion and contraction.

Engineered for TODAY'S NEW CIRCUIT PROTECTION!

Extraordinary factors of fuse strength, security and precision are now imperative in ever-widening fields of new and improved electrical products. Irreplaceable equipment must be conserved. All the specialized resources of Littelfuse's two plants, engineering, design, and construction are employed to meet and anticipate unprecedented requirements.

LITTELFUSES THOROUGHLY PRE-TESTED

"Quicker than a short circuit."

Every Littelfuse is checked by the latest methods and equipment before delivery, for: general workmanship, internal lineup under X-ray, time-current characteristics, resistance, etc.

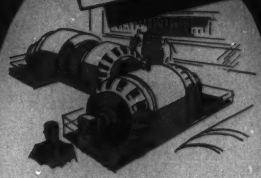
Whatever your problem in circuit protection, Littelfuse will be glad to help.

LITTELFUSE Incorporated

213 Ong St., El Monte, Calif. 4743 Ravenswood Ave., Chicago 40, Ill.

No. 4 in a Series of Factors Essential to Maximum Brush Efficiency

. . . proper adjustment and maintenance is essential to good brush operation



Motors and Generators are usually delivered by the manufacturer with brushes properly installed and adjusted to the correct operating position.

Time, long and severe service, abnormal loads and tough application requirements exact their toll.

Even the best of brushes cannot function efficiently without maintenance and adjustment. Continued good operation requires the spring pressure to be maintained as the brush wears, the brushes and holder be kept clean of dust and dirt, and commutators kept in good condition.

Long life Morganite brushes require a minimum of maintenance and it is wiser to spend minutes checking Morganite brushes than hours changing inferior brushes.

Whether your problems involve main or auxiliary drives in motors, generators, or dynamotors, Morganite can offer data and recommendations to safeguard satisfactory brush service, write

MORGANITE BRUSH CO., Inc.
Long Island City 1, New York

TRADE MARK

MORGANITE BRUSHES

STABILITY

As PERMANENT as the North star, ALSIMAG Steatite Insulators are hard, strong, rigid... impervious to moisture... resistant to heat and cold.

The stability of ALSIMAG steatite ceramics lends rigidity and permanence to electronic circuits—affording constancy under climatic or other operating conditions.

Our Engineering and Research Staff is ready at all times to cooperate in developing the most practical design for insulators and to aid in selecting the most suitable of the numerous ALSIMAG bodies.

Today for our fighting forces, Tomorrow for the miraculous electronic devices of Peace... American Lava is pledged to this Principle: Production to the highest standards... Research to find a better product.

AMERICAN LAVA CORPORATION

CHATTANOOGA 5, TENNESSEE

MADE IN U. S. A.

ARMY E NAVY

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OUT OF TODAY'S RESEARCH TOMORROW IS ENGINEERED

STEATITE CERAMIC INSULATORS

CHARACTERISTICS TAILORED TO YOUR REQUIREMENTS

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Consulting Engineers
Water, Steam and Electric Power Investigations, Design, Supervision of Construction, Valuation and Tests
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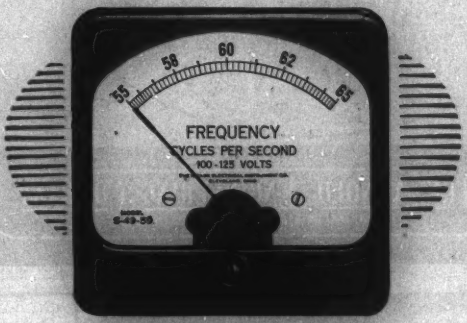

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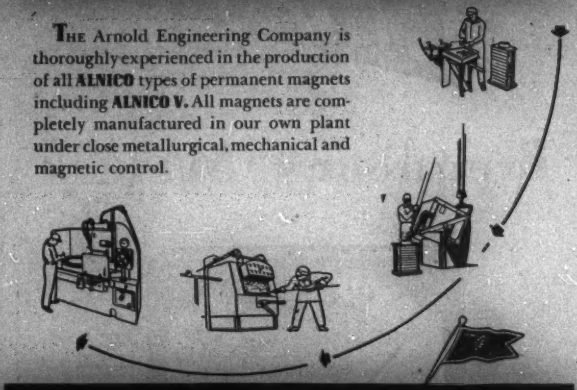

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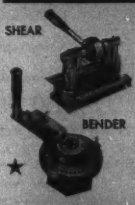

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